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APTI (Air Pollution Training Institute) Course 427: Combustion Evaluation Instructor's Guide

Associated Environmental Consultants
Charlottesville, VA

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APTI
Course 427
Combustion Evaluation

Instructor's Guide

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16. ABSTRACT

This Instructor's Guide is used in conjunction with Course #427, "Combustion Evaluation" as applied to air pollution control situations. The teaching guide was prepared by the EPA Air Pollution Training Institute (APTI) to assist instructors in presenting course #427.

The guide contains sections on the following topics:

- Combustion fundamentals
- Fuel properties
- Combustion system design
- Pollutant emission calculations
- Combustion control
- Gas, oil, & coal burning
- Solid waste & wood burning
- Incineration of wastes
- Sewage sludge incineration
- Flame and catalytic incineration
- Waste gas flares
- Hazardous waste combustion
- NO_x control
- Improved combustion systems

Note: There is also a Student Workbook to be used for homework and in-class problem solving (EPA-450/2-80-064) and a Student Manual for reference and additional subject material (EPA-450/2-80-063)

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Notice

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AIR POLLUTION TRAINING INSTITUTE
MANPOWER AND TECHNICAL INFORMATION BRANCH
CONTROL PROGRAMS DEVELOPMENT DIVISION
OFFICE OF AIR QUALITY PLANNING AND STANDARDS

The Air Pollution Training Institute (1) conducts training for personnel working on the development and improvement of state, and local governmental, and EPA air pollution control programs, as well as for personnel in industry and academic institutions; (2) provides consultation and other training assistance to governmental agencies, educational institutions, industrial organizations, and others engaged in air pollution training activities; and (3) promotes the development and improvement of air pollution training programs in educational institutions and state, regional, and local governmental air pollution control agencies. Much of the program is now conducted by an on-site contractor, Northrop Services, Inc.

One of the principal mechanisms utilized to meet the Institute's goals is the intensive short term technical training course. A full-time professional staff is responsible for the design, development, and presentation of these courses. In addition the services of scientists, engineers, and specialists from other EPA programs governmental agencies, industries, and universities are used to augment and reinforce the Institute staff in the development and presentation of technical material.

Individual course objectives and desired learning outcomes are delineated to meet specific program needs through training. Subject matter areas covered include air pollution source studies, atmospheric dispersion, and air quality management. These courses are presented in the Institute's resident classrooms and laboratories and at various field locations.

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A. INTRODUCTION

This notebook contains the basic materials for use by the course moderator and lecturers teaching "Combustion Evaluation in Air Pollution Control." Among the materials included are:

- Course goals
- Instructional objectives
- Course description and agenda
- Course prerequisite skills
- Intended student population
- General discussion about course presentation
- List of text and other handout materials
- Pretest and post-test with answers
- Class problems and homework assignments
- Lesson plans for each agenda item

The lesson plans include:

- Lesson title, number, and time required
- Lesson goal and objectives
- Student prerequisite skills
- Level of instruction
- Intended students' professional background
- List of support materials and equipment
- Special instructions (if any)
- List of key references
- List of slides
- Lesson content outline keyed to slides and student manual
- Discussion questions

B. GOALS

FOR COMBUSTION EVALUATION IN AIR POLLUTION CONTROL

AIR POLLUTION TRAINING INSTITUTE COURSE NO. 427

The goals of Combustion Evaluation are to provide engineers, other technical and regulatory officials, and others with the knowledge of fundamental and applied aspects of combustion, as well as an overview of the state-of-the-art of combustion technology as it relates to air pollution control work. This knowledge will improve the ability of the participants to perform their work with combustion-related air pollution problems: evaluating actual and potential emissions from combustion sources, performing engineering inspections, and developing recommendations to improve the performance of malfunctioning combustion equipment.

In order to achieve these goals, the participants will be taught to perform calculations typical of those required for Combustion Evaluation.

Emphasis will be placed on those combustion sources and control devices which are frequently encountered by engineers, including selected:

1. Combustion sources burning fossil fuel to generate steam or direct heat,
2. Combustion sources burning liquid and solid waste, and
3. Pollution control devices which utilize combustion for the control of gaseous and aerosol pollutants.

At the conclusion of this course, the participants will be familiar with combustion principles and with the more important design and operational parameters which influence the air pollution emissions from typical combustion sources. Furthermore, they will be able to perform selected fundamental calculations related to emissions quantities and requirements for complete combustion. The participants will understand some of the more important mechanisms by which trace species are formed in and emitted by stationary combustion processes. The participants will understand the ways in which certain design and operation variables may be employed to minimize emissions.

To achieve the maximum benefit from this course, participants should possess some engineering or scientific background.

C. INSTRUCTIONAL OBJECTIVES FOR COMBUSTION EVALUATION IN AIR POLLUTION CONTROL

1. Subject: Introduction to Combustion Evaluation in Air Pollution Control

   Objective: The student will be able to:

   a. identify three major goals of Combustion Evaluation in Air Pollution Control;

   b. list four of the subject areas which will be emphasized in the course (fundamentals of combustion, fuel properties, combustion system design, emission calculations, various combustion equipment topics, NO_X control);

   c. present two reasons for applying the fundamental concepts of combustion when trying to solve combustion evaluation problems in air pollution control;

   d. list three of the important air pollutant emissions which may be limited by combustion control.

2. Subject: Fundamentals of Combustion

   Objective: The student will be able to:

   a. use the basic chemical equations for combustion reactions, with or without excess air, to calculate air requirements and the quantities of combustion products;

   b. apply the ideal gas law to determine volumetric relationships for typical combustion situations;

   c. distinguish between different types of combustion as characterized by carbonic theory (yellow flame) and hydroxylation theory (blue flame);

   d. define heat of combustion, gross and net heating values, available heat, hypothetical available heat, sensible heat, latent heat, and heat content;

   e. determine the available heat obtained from burning fuels at different flue gas exit temperatures and with various amounts of excess air, using generalized correlations;

f. list the chemical elements which combine with oxygen when fuels burn;

g. list the four items necessary for efficient combustion;

h. describe qualitatively the interrelationships between time, temperature, turbulence, and oxygen required for proper combustion of a given fuel;

i. recite the conditions for equilibrium;

j. describe how an excess quantity of one reactant will affect other concentrations at equilibrium;

k. cite the expression for the rate of reaction;

l. identify the Arrhenius equation as a model for the influence of temperature on combustion rate;

m. define the activation energy;

n. describe the mechanism of catalytic activity; and

o. list the reasons for the deterioration of catalytic activity.

3. Subject: Fuel Properties

Objectives: The student will be able to:

a. state the important chemical properties which influence air pollutant emissions;

b. use the tables in the student manual to find representative values for given fuel properties;

c. describe the difference in physical features which limit the rate of combustion for gaseous, liquid, and solid fuels;

d. explain the importance of fuel properties such as flash point and upper and lower flammability limits which relate to safe operation of combustion installations;

e. use either specific or API gravity to determine the total heat of combustion of a fuel oil;

f. describe the influence of variations in fuel oil viscosity on droplet formation and on completeness of combustion and emissions;

g. list the important components in the proximate and ultimate analyses;

h. define "as fired," "as received," "moisture free," and "dry basis" as they apply to the chemical analysis of solid fuels; and

i. explain the significance of ash fusion temperature and caking index in the burning of coal.

4. Subject: Combustion System Design

Objective: The student should be able to:

a. describe the relationship between energy utilization, furnace heat transfer, and excess air as means of furnace temperature control;

b. understand the limits which may be imposed by thermodynamic laws and how these limits dictate choice of energy-recovery devices following the furnace; and

c. calculate the energy required from fuel to meet an output energy requirement.

5. Subject: Pollution Emission Calculations

Objective: The student should be able to:

a. describe the nature and origin of most of the published emission factors and state what is necessary for more precise estimates of emissions from a specific installation with specified design features;

b. apply the proper method for using emission factors to determine estimates of emissions from typical combustion sources;

c. define and distinguish between concentration standards (C_{vs} and C_{ms}), pollutant mass rate standards (PMR_s), and process standards (E_s);

d. use average emission factors to estimate the emissions from typical combustion installations;

e. calculate the degree of control required for a given source to be brought into compliance with a given emission standard;

f. perform calculations using the relationships between anticipated SO_2 emissions and the sulfur content of liquid and solid fuels;

g. identify the proper equation for computing excess air from an Orsat analysis of the flue gas of a combustion installation;

h. state the reasons for expressing concentrations at standard conditions of temperature pressure, moisture content, and excess air;

i. identify and use the proper factors for correcting field measurements to a standard basis, such as 50% excess air, 12% CO_2, and 6% O_2; and

j. use F-factors to estimate emissions from a combustion source.

6. Subject: Combustion Control and Instumentation

Objective: The student will be able to:

a. list the important variables (steam pressure, steam flow rate, gas temperature) which may serve as the controlled variables used to actuate fuel/air controls for combustion systems;

b. describe the primary purpose of a control system which is to maintain combustion efficiency and thermal states;

c. understand the interrelationships between varying load (energy output) requirements and both fuel/air flow and excess air;

d. identify instrument readings indicating improper combustion or energy transfer; and

e. describe the influence of excess air (indicated by O_2 in stack gases) on the boiler efficiency, fuel rate, and economics of a particular boiler installation.

7. Subject: Gaseous Fuel Burning

Objective: The student will be able to:

a. describe the functions of the gas burner;

b. define pre-mix and its influence on the type of flame;

c. list burner design features and how these affect the limits of stable flame operating region;

d. name four different types of gas burners and their special design features;

e. cite typical gas furnace, breeching and stack operating temperatures, pressures, and gas flow velocities;

f. describe the relationship between flue gas analyses and the air-to-fuel ratio;

g. list the causes and describe the signs of malfunctioning gas-burning devices; and

h. describe techniques used to correct a malfunctioning gas-burning device.

8. Subject: Fuel Oil Burning

Objective: The student will be able to:

a. describe the important design and emission characteristics of oil burners using air, steam, mechanical (pressure), and rotary-cup atomization;

b. describe the influence of temperature on oil viscosity and atomization;

c. describe how vanadium and sulfur content in fuel oil influence furnace corrosion and air pollution emissions;

d. describe burner nozzle maintenance and its influence on air pollutant emissions from oil combustion installations; and

e. locate and use tabulated values of oil fuel properties and pollutant factors to compute uncontrolled emissions from oil-burning sources

9. Subject: Direct-Flame and Catalytic Incineration

Objective: The student will be able to:

a. cite examples of air pollution sources where direct-flame and catalytic afterburners are used to control gaseous emissions;

b. describe the influence of temperature on the residence time required for proper operation of afterburners;

c. apply fundamental combustion calculations to determine the auxiliary fuel required for direct-flame and catalytic incineration with and without energy recovery;

d. perform the necessary calculations to determine the proper physical dimensions of an afterburner for a specific application;

e. list three reasons for loss of catalytic activity and ways of preventing such loss; and

f. cite methods available for reducing afterburner operating costs.

10. Subject: Coal Burning

Objective: The student will be able to:

a. describe the design characteristics and operating practice of coal burning equipment, including overfeed, underfeed, and spreader stokers, as well as pulverized and cyclone furnaces;

b. discuss the parameters that influence the design of overfire and underfire air (in systems which burn coal on grates) and for primary and secondary air (in systems which burn coal in suspension);

c. describe the influence of the amount of volatile matter and fixed carbon in the coal on its proper firing in a given furnace design; and

d. describe how changing the ash content and the heating value of coal can influence the combustion as well as the capacity of a specified steam generator.

11. Subject: Solid Waste and Wood Burning

Objective: The student will be able to:

a. list the important similarities and differences in both the physical and chemical properties of solid waste, wood waste, and coal;

b. describe the mechanical configurations required to complete combustion of solid waste and wood waste and compare with those for burning coal; and

c. describe the unique combustion characteristics and emissions from burning unprepared solid waste and refuse-derived fuel.

12. Subject: Controlled-Air Incineration

Objective: The student will be able to:

a. describe the combustion principles and pollution emission characteristics of controlled-air incinerators contrasted with those of single and multiple-chamber designs;

b. identify operating features which may cause smoke emission from controlled-air incinerators; and

c. relate the temperature of gases leaving the afterburner to the amount of auxiliary fuel needed by the afterburner.

13. Subject: Combustion of Hazardous Wastes

Objective: The student will be able to:

a. cite special requirements associated with the combustion of hazardous liquid and solid wastes;

b. recite the special requirements for treating the combustion products to control pollutant emissions from incineration operations;

c. list examples of substances and/or elements which cannot be controlled by incineration;

d. describe the fuel requirements necessary to dispose hazardous waste materials; and

e. list a number of hazardous waste materials (including polychlorinated biphenyls — PCB's — pesticides, and some other halogenated organics) which may be disposed of successfully through proper liquid incineration devices; give the required temperatures and residence times to achieve adequate destruction.

14. Subject: NO_X Control

Objective: The student will be able to:

a. identify three of the major stationary sources of NO_X emissions;

b. locate and use emission factors to estimate the amount of NO_X emitted by a potential combustion source;

c. describe the difference between mechanisms for forming "Thermal NO_X" and "Fuel NO_X";

d. describe various techniques for NO_X control: flue-gas recirculation, two-stage combustion, excess air control, catalytic dissociation, wet-scrubbing, water injection, and reduced fuel burning rate; and

e. state the amount of NO_X control available from particular examples of combustion modification.

15. Subject: Improved Combustion through Design Modification

Objective: The student will be able to:

a. state the benefits of proper maintenance and adjustment of residential oil-combustion units;

b. list three important features to check during the maintenance of commercial oil-fired burners;

c. discuss the difference between "minimum O_2" and "lowest practical O_2" and why these are important in industrial boilers;

d. list two reasons why a burner may have a higher "minimum O_2" level than the typical value; describe what remedies may be available;

e. indicate the effect of the combustion modification techniques on thermal efficiency: lowering excess air, staged-air combustion; reduced combustion-air preheat, and flue-gas recirculation; and

f. discuss why NO_x control from coal-fired utility boilers is more difficult to achieve than from similar oil or gas units.

16. Subject: Waste Gas Flares (Optional)

Objective: The student will be able to:

a. calculate the carbon-to-hydrogen ratio of a waste-gas stream and determine when and how much steam will be required for smokeless-flare operation;

b. understand the difference between elevated and ground-level flares and the design considerations which underlie the choice of one or the other; and

c. describe provisions for leveling waste-gas flow rates from intermittent sources.

17. Subject: Municipal Sewage Sludge Incineration (Optional)

Objective: The student will be able to:

a. list and discuss the air pollutants emitted in incineration of sewage sludge;

b. describe special design features required to burn wet sewage sludge fuel;

c. describe the combustion-related activity occurring in each of the four zones of the multiple-hearth sewage sludge incinerators;

d. discuss the options of combustion air preheating, flue gas reheating, and energy recovery; and

e. list two important operational problems which can adversely influence air pollution emissions.

D. COURSE BACKGROUND AND DESCRIPTION

In 1966 the Air Pollution Training Program of the Robert A. Taft Sanitary Engineering Center in Cincinnati, Ohio established the course "Combustion Evaluation, Sources and Control Devices," No. 427. This course was originally taught by personnel of the Air Pollution Training Institute with the aid of various guest lecturers.

Between June 1972 and September 1978, Associated Environmental Consultants of Charlottesville, Virginia taught "Combustion Evaluation" twenty-seven times under contract with the U. S. Environmental Protection Agency.

In 1978 Associated Environmental Consultants contracted to develop new objectives and instructional resource materials so that the course could be taught by technically capable persons at various regional air pollution control training centers throughout the United States.

New course goals, instructional objectives, agenda, and intended student populations were selected following discussion meetings with selected advisers. These meetings were held in EPA facilities at Research Triangle Park, NC (April 7, 1978 and June 1, 1978), Chicago, IL (May 16, 1978), and San Francisco, CA (May 17, 1978). Attending the meetings were the EPA project officer, James O. Dealy; a representative from Associated Environmental Consultants; and at the Chicago and San Francisco meetings, representatives selected from appropriate federal, state, and local air pollution control agencies. The June 1, 1978 meeting was attended by representatives of the Air Pollution Training Institute, Northrop Services, Inc., the EPA Industrial Environmental Research Laboratory, as well as other EPA research and regulatory divisions.

The instructional resource materials which were developed include this Course Moderator's Manual; the student manual, entitled: Combustion Evaluation in Air Pollution Control; and the Workbook for Combustion Evaluation in Air Pollution Control.

The course moderator will note that the course agenda (see Section 5) is arranged in a sequential format, which may be taught as indicated in the agenda, or may be rearranged to meet the needs of various geographical regions, as well as the available time which a particular group of students has to participate in training activities.

Lessons 1 through 8 provide a module of instructional material on the chemistry of combustion, containing specific information about fuels and combustion calculations. Many of the participants will have been previously introduced to this fundamental information in college chemistry and physics courses. It is included in the course as a review, because of its importance in combustion and pollution emission calculations. In addition, the fundamental combustion concepts must be understood in order to evaluate other combustion-related air pollution problems. Depending on the particular student population, additional time may be used on these topics. These areas may be omitted from the course for students who require only the advanced information; however, they should read Chapter 1, 2, and 3 prior to their attendance.

Lessons 9 through 14 provide a module of instructional material on combustion design and pollution emission computations. This module will be difficult for any student who does not have an engineering or equivalent background. However, field enforcement personnel and technicians will profit from this if they possess engineering computational abilities.

Lessons 15 through 25 provide a module for instruction on the design and operating features of typical combustion equipment which are important for good combustion and air pollutant control.

Lessons 26 through 30 provide an instructional module containing material which is of specific technical interest. Two optional topics (flares and sewage sludge incineration) are provided for the particular interests of some regions or student populations. These topics may be substituted in the place of other topics (e.g., controlled-air incineration and combustion of hazardous waste), or they may be added to extend the course. The course moderator will use his or her judgment and knowledge of the student population in this matter.

Additionally the course moderator may use discretion to revise the course agenda, provide more time for some lessons and less time for others, or make the course longer or shorter. The students' background and their training needs will be the determining factors in the moderator's decision of the lesson topics. It is recommended that the sequence given in the first twenty-four lessons be followed, to accommodate the prerequisites of each lesson. Sequence rearrangement and substitution of optional lessons after Lesson 24 will not cause disruption, except that Lesson 28 should follow Lesson 27.

A pre-test and post-test have been included to measure how effectively the instructional objectives have been achieved.

E. AGENDA FOR COMBUSTION EVALUATION IN AIR POLLUTION CONTROL

DAY & TIME	SUBJECT
Monday	
8:30 – 9:30	Registration and Pre-Test
9:30 – 10:00	Introduction to Combustion Evaluation
10:00 – 10:50	Fundamentals of Combustion I – Basic Chemistry
11:10 – 12:00	Fundamentals of Combustion II – Thermochemical Relationships
1:00 – 1:30	Film – "Three T's of Combustion"
1:30 – 2:20	Reaction Kinetics
2:40 – 3:20	Fuel Properties
3:20 – 4:30	Problem Session I
4:30	Homework Assignment: Problem I.5
Tuesday	
8:30 – 9:00	Review Homework and Pre-Test Results
9:00 – 10:00	Combustion System Design
10:15 – 11:15	Problem Session II
11:15 – 12:00	Pollution Emission Calculations I
1:00 – 1:45	Problem Session III
1:45 – 3:15	Pollution Emission Calculations II
3:30 – 4:30	Problem Session IV
4:30	Homework Assignment: Problem II.2, IV.3, IV.5

DAY & TIME	SUBJECT
Wednesday	
8:30 – 8:45	Homework Review
8:45 – 9:15	Introduction to Combustion Control
9:15 – 10:00	Film – "Boilers and Their Control"
10:15 – 11:00	Combustion Installation Instrumentation
11:00 – 12:00	Gaseous Fuel Burning
1:00 – 2:00	Fuel Oil Burning
2:00 – 2:30	Film – "Combustion for Control of Gaseous Pollutants"
2:45 – 3:45	Direct Flame and Catalytic Incineration
3:45 – 4:30	Problem Session V
4:30	Homework Assignment: Problem V.2
Thursday	
8:30 – 8:45	Homework Review
8:45 – 10:30	Coal Burning
10:45 – 12:00	Solid Waste and Wood Burning
1:00 – 2:00	Problem Session VI
2:15 – 3:15	Controlled Air Incineration (or optional topic)
3:30 – 4:30	Combustion of Hazardous Waste (or optional topic)
4:30	Homework Assignment: Problem VI.2
Friday	
8:30 – 8:45	Homework Review
8:45 – 9:45	NO_X Control Theory
10:00 – 11:00	Combustion Modifications
11:00 – 12:00	Post-Test
12:00	Course Concludes

Optional Topic 1: Flares
Optional Topic 2: Sewage Sludge Incineration

F. COURSE PREREQUISITE SKILLS

Prerequisites for Course 427 include completion of Course 452, or equivalent experience, and one of the following: college-level training in physical science, engineering, or mathematics.

G. INTENDED STUDENT POPULATION

Because this course is designed around student participation, it is important that students selected for the course have the proper background so that they may both benefit from, and contribute to, the course presented.

Combustion Evaluation in Air Pollution Control is prepared for engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control. The course will be useful for the above personnel who work in federal, state, and local control agencies as well as for industry.

The ideal class size is 20 to 35 students. There should be enough students to facilitate good discussions and not so many that some will not be able to ask questions or clearly see projected materials or the chalkboard.

H. DISCUSSION ABOUT COURSE PRESENTATION

Instructors - The three most important criteria in the faculty selection for this course are: (a) knowledge of combustion fundamentals and practice related to air pollution control; (b) practical experience with evaluation of air pollution emissions from combustion sources; and (c) experience (and ability) to use lecture and problem session techniques to instruct adults. In addition, the Course Moderator should select instructors known to have positive attitudes toward air pollution control regulations.

It would be particularly helpful if instructors were able to sit in on earlier offerings of the course in order to gain an appreciation of the background and needs of typical students.

The Course Moderator should schedule a briefing session before any instructor is permitted to go before a class. This session should cover a brief review of the overall course and the lesson objectives. Discussion should ensure that the instructor is well-prepared and comfortable with the material and techniques to be used.

Lesson plans should be distributed in advance to the faculty to give adequate lead time for preparation. Preparation must include the study of the appropriate sections of the moderator's manual, visual aids, student manual, student workbook, and key references noted in the lesson content outline.

Each lesson plan outlined is designed for a limited time. Instructors should be cautioned to observe time schedules. There is no reason why instructors cannot vary the format or content of any given lesson, as long as lesson objectives are met. However, all variations should be to encourage greater student participation.

Physical Setting — In selecting the physical setting for this course, the course moderator must anticipate several special requirements. Students will perform calculations in problem session, so tables with comfortable chairs will be needed. Students should not be crowded together, as it would interfere with their use of the course manual and workbook to solve class problems and take notes.

Projection slides will be used to illustrate lectures, so proper projection equipment, screen, and room darkening will be required. The students will be referring to particular materials in their manuals during the lectures, so at least some partial lighting may be required, even while the slides are being shown. A chalkboard large enough to present computational problem solutions also will be needed.

Checklist of Activities for Presenting the Course — The following checklist will serve as a guide to assure consideration of special items:

1. Pre-Course Responsibilities:

    ___ a. Reserve and confirm classroom, including size, "set-up," location, and costs (if any).

___ b. Select, contact, and confirm all faculty (speakers) for the course. Forward materials to them.

___ c. Reserve hotel accommodations for faculty (if needed).

___ d. Arrange for food services (i.e., coffee breaks, water, etc.)

___ e. Review and modify program curricula to recognize regional interest, based on assessment of need.

___ f. Prepare and reproduce final ("revised" if appropriate) copy of the agenda.

___ g. Reproduce final registration roster.

___ h. Prepare name badges and name "tents" for students and faculty.

___ i. Identify, order, and confirm all A-V equipment needed.

___ j. Obtain sufficient copies of EPA Student Manuals, Workbooks, Pre-Test, and Post-Test.

___ k. Pack and ship supplies and materials to the course location prior to beginning of course (if appropriate).

2. On-Site Course Responsibilities:

___ a. Determine and check on final room arrangements (i.e., tables, chairs, lectern, water, cups, etc.).

___ b. Set up A-V equipment required each day and brief operator (if supplied).

___ c. Alert receptionist, watchmen, etc., of name, location, and schedule of the program.

___ d. Set up and handle final registration check-in procedures.

___ e. Conduct a new speaker(s) briefing session on a daily basis.

___ f. Verify and make final coffee arrangements (where appropriate).

___ g. Make a final check on arrival of guest speakers (instructors) for the day.

___ h. Collect student evaluation critiques at the end of the course.

___ i. Award certificates on last day of course.

3. Post-Course Responsibilities

___ a. Request expense statements from faculty; order and process checks.

___ b. Write thank-you letters and send checks to paid faculty.

___ c. Write thank-you letters to non-paid guest speakers.

___ d. Prepare evaluation on each course (including instructors, content, facilities, etc.)

___ e. Make sure A-V equipment is returned.

___ f. Return unused materials to the appropriate office.

I. LIST OF TEXTS AND OTHER HANDOUT MATERIALS

The following lesson materials should be available for each student taking the course:

1. Course Manual: Combustion Evaluation in Air Pollution Control by J. T. Beard, F. A. Iachetta, and L. U. Lilleleht.
2. Workbook for Combustion Evaluation in Air Pollution Control by J. T. Beard, F. A. Iachetta, and L. U. Lilleleht.
3. Pre-Test
4. Post-Test
5. Final Registration Roster
6. Student Critique Sheets
7. Course Certificates

J. PRE-TEST AND POST-TEST

The Pre-Test and the Post-Test are found as part of Lesson Plan 31. Answers to each are provided.

K. CLASS PROBLEMS AND HOMEWORK ASSIGNMENTS

The class problems for Problem Sessions I through VI are found in the Workbook in Chapters I through VI, respectively. Answers to the problems are found as part of Lesson Plans 7, 10, 12, 14, 21, and 24.

L. MASTER LIST OF SLIDES (Pages 20 through 38)

M. LESSON PLANS FOR EACH AGENDA ITEM

The detailed lesson plans for each agenda item follow the master list of slides.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 1: INTRODUCTION TO COMBUSTION EVALUATION IN AIR POLLUTION CONTROL
427-1-1	GOALS
427-1-2	COURSE WILL EMPHASIZE
427-1-3	FUEL BURNING SOURCES
427-1-4	COMBUSTION OF WASTE MATERIALS
427-1-5	AIR POLLUTION EMISSIONS CONTROLLED BY COMBUSTION
427-1-6	AT THE CONCLUSION OF THE COURSE
	LESSON 2: FUNDAMENTALS OF COMBUSTION II - BASIC CHEMISTRY
427-2-1	FUNDAMENTALS OF COMBUSTION
427-2-2	GENERAL COMBUSTION REACTION
427-2-3	THREE T'S OF COMBUSTION
427-2-4	COMPLETE COMBUSTION
427-2-5	THEORETICAL AIR FOR COMPLETE COMBUSTION
427-2-6	FLAMMABILITY LIMITS OF COMBUSTIBLE VAPORS IN AIR
427-2-7	STANDARD CONDITIONS
427-2-8	IDEAL (PERFECT) GAS LAW
427-2-9	CHARLES' AND BOYLE'S LAWS
427-2-10	SELECTED REACTIONS IN COMBUSTION SEQUENCE
427-2-11	CARBONIC THEORY
427-2-12	HYDROXYLATION THEORY
427-2-13	YELLOW FLAME
427-2-14	BLUE FLAME
427-2-15	STEAM INJECTION TO YELLOW FLAME

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 3: FUNDAMENTALS OF COMBUSTION II - THERMOCHEMICAL RELATIONSHIPS
427-3-1	GROSS HEATING VALUE
427-3-2	NET HEATING VALUE
427-3-3	ADIABATIC STEADY STATE HEAT BALANCE
427-3-4	HEAT BALANCE ACROSS SYSTEM BOUNDARY WITHOUT HEAT LOSS
427-3-5	GENERALIZED COMPARISON OF PURE HYDROCARBON FUELS IN COMPLETE COMBUSTION
427-3-6	AVAILABLE HEATS FRO SOME TYPICAL FUELS
427-3-7	AVAILABLE HEATS WITH EXCESS AIR
427-3-8	FURNACE LOSSES
427-3-9	SUMMARY OF HEAT BALANCE TERMS
	LESSON 4: FILM: 3 T's OF COMBUSTION (NO SLIDES REQUIRED)
	LESSON 5: REACTION KINETICS
427-5-1	CHEMICAL REACTION RATES
427-5-2	EQUILIBRIUM CONDITIONS
427-5-3	TRANSITION STATE CONCEPT
427-5-4	TEMPERATURE EFFECT ON REACTION RATE
427-5-5	TYPICAL CATALYSTS AND THEIR SUPPORTS
427-5-6	STEPS IN CATALYTIC REACTION SEQUENCE
427-5-7	SCHEMATIC OF THE CATALYTIC REACTION SEQUENCE
427-5-8	ARRHENIUS PLOT WITH AND WITHOUT CATALYST
427-5-9	DETERIORATION OF PLATINUM CATALYTIC ACTIVITY

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 6: FUEL PROPERTIES
427-6-1	GASEOUS FUELS HAVE RATE OF COMBUSTION
427-6-2	HIGHER HEATING VALUE
427-6-3	LOWER HEATING VALUE
427-6-4	API GRAVITY
427-6-5	APPROXIMATE VISCOSITY OF FUEL OIL
427-6-6	PROXIMATE ANALYSIS OF SELECTED COAL
427-6-7	ULTIMATE ANALYSIS OF SELECTED COAL (AS RECEIVED)
427-6-8	ULTIMATE ANALYSIS OF SELECTED COAL (DRY BASIS)
427-6-9	SELECTED SIZE DISTRIBUTION AND MOISTURE OF HOGGED FUELS
	LESSON 7: PROBLEM SESSION I (No slides required)
	LESSON 8: REVIEW OF HOMEWORK (No slides required)
	LESSON 9: COMBUSTION SYSTEMS DESIGN
427-9-1	FURNACE DESIGN CONSIDERATIONS
427-9-2	SYSTEM ENERGY DISTRIBUTION
427-9-3	STEAM GENERATOR ENERGY DISTRIBUTION
427-9-4	ENERGY DISTRIBUTION
	LESSON 10: PROBLEM SESSION II (No slides required)

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 11: POLLUTION EMISSIONS - CALCULATIONS I
427-11-1	NOMENCLATURE OF STANDARDS
427-11-2	C_{ms}, MASS STANDARD
427-11-3	POLLUTANT MASS RATE STANDARD
427-11-4	PROCESS STANDARD
427-11-5	EMISSION FACTORS FOR FUEL OIL COMBUSTION
427-11-6	EMISSION FACTORS FOR NATURAL GAS COMBUSTION
427-11-7	SO_2 EMISSION ESTIMATE, GIVEN:
427-11-8	EMISSION ESTIMATE FROM BASIC CHEMISTRY
427-11-9	EMISSION CALCULATION
427-11-10	RECOMPUTATION WITH EMISSION FACTOR
427-11-11	PROCESS EMISSION
427-11-12	UNCONTROLLED PARTICULATE EMISSION ESTIMATE
427-11-13	FRACTIONAL COLLECTIONAL EFFICIENCIES OF PARTICULATE CONTROL EQUIPMENT
	LESSON 12: PROBLEM SESSION III (No slides required)

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 13: POLLUTION EMISSION CALCULATIONS II
427-13-1	GAS VOLUME CORRECTIONS
427-13-2	GAS CORRECTIONS FOR CONCENTRATION
427-13-3	GAS CORRECTIONS FOR DENSITY
427-13-4	EXCESS AIR CORRECTIONS
427-13-5	CORRECTIONS TO 50% EXCESS AIR
427-13-6	CORRECTIONS TO 12% CO_2
427-13-7	CORRECTIONS TO 6% O_2
427-13-8	EXCESS AIR PERCENT
427-13-9	EXAMPLE WITHOUT EXCESS AIR
427-13-10	EXAMPLE WITH EXCESS AIR
427-13-11	EXCESS AIR FROM ORSAT ANALYSIS
427-13-12	SAMPLE OF ORSAT DATA APPLICATION
427-13-13	CALCULATE % EXCESS AIR
427-13-14	EXAMPLE PROCESS EMISSION STANDARD
427-13-15	DEFINITION OF AN "E" STANDARD PROBLEM
427-13-16	SOLUTION OF SAMPLE "E" PROBLEM
427-13-17	ALLOWABLE EMISSION
427-13-18	ACTUAL PARTICULATE RATE
427-13-19	F-FACTOR CONCEPT
427-13-20	EMISSION IN TERMS OF F-FACTOR
427-13-21	EQUATIONS FOR F_c FACTOR
427-13-22	EQUATION FOR F_o FACTOR
427-13-23	TABLE OF F-FACTORS

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 14: PROBLEM SESSION IV (No slides required)
	LESSON 15: INTRODUCTION TO COMBUSTION CONTROL
427-15-1	SCHEMATIC OF STEAM-FLOW ORIFICE STATION
427-15-2	ACTUAL STEAM-FLOW ORIFICE STATION
427-15-3	STEAM-FLOW DIFFERENTIAL SENSING AND TRANSFER UNIT
427-15-4	AUTOMATIC FORCED-DRAFT FAN INLET LOUVER CONTROL
427-15-5	AUTOMATIC GAS-FLOW CONTROL VALVE
427-15-6	DIAGRAM OF A COMBUSTION CONTROL FOR A SPREADER-STOKER FIRED BOILER
427-15-7	DIAGRAM OF A COMBUSTION CONTROL FOR A GAS- AND OIL-FIRED BOILER
427-15-8	DIAGRAM OF A COMBUSTION CONTROL FOR A PULVERIZED-COAL FIRED BOILER
427-15-9	DIAGRAM OF A COMBUSTION CONTROL FOR A CYCLONE-FIRED BOILER
	LESSON 16: COMBUSTION INSTALLATION INSTRUMENTATION
427-16-1	STEAM-FLOW AIR-FLOW METER AND CHART
427-16-2	DRAFT GUAGES ON SPREADER STOKER-FIRED BOILER INSTRUMENT PANEL
427-16-3	GAS AND WATER TEMPERATURES OF ECONOMIZER
427-16-4	INSTRUMENT PANEL WITH REMOTE STACK SMOKE INDICATOR
427-16-5	SKETCH OF REMOTE STACK SMOKE INDICATOR
427-16-6	RANEREX CONTINUOUS CO_2 METER
427-16-7	TYPICAL O_2 READINGS
427-16-8	TYPICAL CO_2 READINGS
427-16-9	EFFECT OF EXCESS AIR (FLUE GAS CO_2) ON COMBUSTION EFFICIENCY
427-16-10	IMPROVED EFFICIENCY CASCADE

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 17: GASEOUS FUEL BURNING
427-17-1	BLUE FLAME
427-17-2	YELLOW FLAME
427-17-3	ATMOSPHERIC BURNERS - FLAME STABILITY
427-17-4	ATMOSPHERIC PREMIX TYPE GAS BURNER
427-17-5	MULTI-FUEL OIL GASIFYING BURNER
427-17-6	FURNACE HEAT RELEASE RATE
427-17-7	COMPARITIVE FURNACE SIZES
427-17-8	TYPICAL BREECHING AND STACK CONDITIONS
427-17-9	VELOCITY IN CONVECTIVE SECTION
427-17-10	FLUE GAS ANALYSIS

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 18: FUEL OIL BURNING
427-18-1	PURPOSE OF FUEL OIL BURNING
427-18-2	REQUIREMENTS FOR COMPLETE COMBUSTION
427-18-3	MODE OF COMBUSTION OF FUEL OIL DROPLETS
427-18-4	APPROXIMATE VISCOSITY OF FUEL OILS
427-18-5	TYPICAL EXCESS AIR LEVELS
427-18-6	VOLUMETRIC HEAT RELEASE RATES AND RESIDENCE TIMES
427-18-7	SCOTCH-MARINE BOILER
427-18-8	INTEGRAL FURNACE BOILER
427-18-9	WATER WALL TUBES
427-18-10	WATER WALL TUBES
427-18-11	INTEGRAL FURNACE BOILER, TYPE D
427-18-12	VERTICALLY-FIRED OIL BURNING FURNACE
427-18-13	TEMPERATURES IN BOILER OF PREVIOUS SLIDE
427-18-14	BOILER, TANGENTIALLY FIRED
427-18-15	WATER-WALL FURNACE CROSS SECTION (TANGENTIALLY FIRED)
427-18-16	ATOMIZING CHARACTERISTICS OF DIFFERENT BURNERS
427-18-17	ROTARY CUP BURNER
427-18-18	HIGH-PRESSURE ATOMIZER (DOMESTIC)
427-18-19	LOW-PRESSURE AIR ATOMIZER
427-18-20	LOW-PRESSURE AIN ATOMIZER SKETCH
427-18-21	LOW-PRESSURE AIR ATOMIZER MOUNTED IN COMMERCIAL FURNACE
427-18-22	TANGENTIAL SWIRL NOZZLES
427-18-23	SWIRL DEVICE FOR SECONDARY AIR

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 18: FUEL OIL BURNING, continued
427-18-24	HIGH-PRESSURE ATOMIZER
427-18-25	MECHANICAL ATOMIZATION (WITH RETURN FLOW, SPILL BACK)
427-18-26	EXAMPLES OF RETURN FLOW HIGH AND LOW FIRE
427-18-27	STEAM ATOMIZING (INTERNAL MIX)
427-18-28	STEAM ATOMIZING (INTERNAL MIX)
427-18-29	INTERNAL MIX STEAM ATOMIZING NOZZLE
427-18-30	INTERNAL MIX STEAM ATOMIZING NOZZLE
427-18-31	INTERNAL MIX STEAM ATOMIZING NOZZLE
427-18-32	STEAM OR AIR ATOMIZING BURNER (EXTERNAL MIX)
427-18-33	INFLUENCE OF DRAFT - CASE HISTORY
427-18-34	SMOKE - CO_2 CHARACTERISTICS

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 19: FILM - "COMBUSTION FOR CONTROL OF GASEOUS EMISSIONS" (No slides required)
	LESSON 20: DIRECT FLAME AND CATALYTIC INCINERATION
427-20-1	CONTROL OF OBJECTIONABLE GASES AND VAPORS
427-20-2	COMBUSTION EQUIPMENT
427-20-3	DIRECT FLAME OXIDATION
427-20-4	COUPLED EFFECTS OF TEMPERATURE AND TIME ON HYDROCARBON OXIDATION RATE
427-20-5	TYPICAL THERMAL AFTERBURNER EFFECTIVENESS FOR HYDROCARBON AND CARBON MONOXIDE MIXTURES
427-20-6	INDUCED DRAFT FUME INCINERATOR
427-20-7	DIRECT-FLAME AFTERBURNER
427-20-8	CATALYTIC AFTERBURNER SCHEMATIC
427-20-9	OXIDATION TEMPERATURE
427-20-10	INDUSTRIAL APPLICATIONS OF CATALYTIC COMBUSTION
427-20-11	TYPICAL CATALYSTS AND THEIR SUPPORTS
427-20-12	LOSS OF CATALYST ACTIVITY
427-20-13	CATALYTIC INCINERATOR WITH RECYCLE AND HEAT ECONOMIZER
427-20-14	CERAMIC BED REGENERATIVE-TYPE INCINERATOR AND HEAT RECOVERY SYSTEM

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 21: PROBLEM SESSION V: (No slides required)
	LESSON 22: COAL BURNING
427-22-1	COAL RESERVES - BILLIONS OF TONS
427-22-2	COAL SOURCE DISTRIBUTION
427-22-3	COAL ANALYSIS
427-22-4	INFLUENCE OF FIXED CARBON AND VOLATILE MATTER ON FIRING EQUIPMENT
427-22-5	CHAIN GRATE STOKER
427-22-6	VIBRATING GRATE STOKER
427-22-7	UNDERFEED SINGLE RETORT STOKER
427-22-8	SECTION THRU UNDERFEED STOKER
427-22-9	UNDULATING GRATE STOKER
427-22-10	PULVERIZED COAL BURNER
427-22-11	MULTIFUEL BURNER
427-22-12	SPREADER STOKER SCHEMATIC
427-22-13	SPREADER STOKER
427-22-14	CYCLONE FURNACE
427-22-15	PULVERIZED COAL-FIRED BOILER
427-22-16	CYCLONE FURNACE
427-22-17	BOILER WITH CYCLONE FURNACE
427-22-18	COMBUSTION AIR - THEORETICAL
427-22-19	COMBUSTION AIR - GIVEN ULTIMATE ANALYSIS
427-22-20	EFFECT OF COAL FIRING RATE AND SIZE CONSIST
427-22-21	EFFECT OF EXCESS AIR (FLUE GAS CO_2) ON COMBUSTION EFFICIENCY

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 23: SOLID WASTE AND WOOD BURNING
427-23-1	AVERAGE COMPOSITION OF MUNICIPAL WASTE
427-23-2	AVERAGE ULTIMATE ANALYSIS
427-23-3	WASTE IN AN INCINERATOR STORAGE
427-23-4	HOG FUEL STORAGE PILE
427-23-5	CLARIFIER SLUDGE
427-23-6	ULTIMATE ANALYSIS OF DRY HOGGED FUEL
427-23-7	SIZE AND MOISTURE CONTENT OF HOGGED FUEL COMPONENTS
427-23-8	HEATING VALUES OF BARK AND WOOD
427-23-9	HIGHER HEAT VALUE OF MUNICIPAL WASTE COMPONENTS
427-23-10	FLOW CHART - REFRACTORY WALL INCINERATOR
427-23-11	CHAIN GRATE
427-23-12	RECIPPOCATING GRATES
427-23-13	REVERSE RECIPROCATING GRATE
427-23-14	WASTE-FIRED BOILER WITH BARREL GRATE
427-23-15	DIAGRAM OF AIR-SWEPT SPREADER STOKER NOZZLE
427-23-16	AIR-SWEPT SPREADER ON WOOD-FIRED BOILER
427-23-17	ENERGY RELEASE RATES - SOLID WASTE AND WOOD WASTES
427-23-18	HARRISBURG INCINERATOR
427-23-19	SOLID WASTE BOILER WITH RECIPROCATING GRATES
427-23-20	DUTCH OVEN FIRED BOILER
427-23-21	FUEL CELL FIRED WOOD WASTE BOILER
427-23-22	INCLINED GRATE WOOD WASTE BOILER
	LESSON 24: PROBLEM SESSION VI (No slides required)

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 25: CONTROLLED AIR INCINERATOR
427-25-1	AVERAGE EMISSION FACTORS FOR REFUSE COMBUSTION
427-25-2	FLUE FED SINGLE CHAMBER INCINERATOR
427-25-3	APARTMENT HOUSE INCINERATOR WITH SEPARATE STORAGE BIN
427-25-4	MULTIPLE-CHAMBER RETORT INCINERATOR
427-25-5	MULTIPLE-CHAMBER IN-LINE INCINERATOR
427-25-6	MULTIPLE-CHAMBER IN-LINE INCINERATOR
427-25-7	CONTROLLED AIR INCINERATOR
427-25-8	CONTROLLED PROPORTIONATE AIR DISTRIBUTION
427-25-9	AIR DELIVERY BLOWER
427-25-10	PRIMARY CHAMBER PRODUCES VOLATILE GASES
427-25-11	SECONDARY CHAMBER
427-25-12	TEMPERATURE CONTROLLER
427-25-13	RELATIVE SIZE OF PRIMARY AND SECONDARY CHAMBERS
427-25-14	FACTORY MANUFACTURED
427-25-15	MODULAR UNIT AT MUNICIPAL FACILITY
427-25-16	CHARGING OF AUTOMATIC FEED HOPPER
427-25-17	ASH REMOVAL DOORS
427-25-18	AUXILIARY FUEL BURNER
427-25-19	MULTIPLE AUXILIARY BURNERS FOR PRIMARY CHAMBER OF PATHOLOGICAL WASTE INCINERATOR
427-25-20	COMPACT WASTE CHARGE
427-25-21	CHARGING WITH OPEN DOOR
427-25-22	MODIFY CONTROLLER TEMPERATURE SETTING
427-25-23	DAMAGED REFRACTORY AND UNDERFIRE AIR PIPE
427-25-24	UNDERFIRE AIR SUPPLY ORIFICES

SLIDE NUMBER	TITLE OF SLIDE
427-25-25	INCINERATOR WITH STEAM GENERATION
427-25-26	INCINERATOR WITH CONTINUOUS FEED AND ASH REMOVAL
	LESSON 26: COMBUSTION OF HAZARDOUS WASTE
427-26-1	COMPARISON OF THERMAL DESTRUCTION OF PESTICIDES AND PCB's
427-26-2	THERMAL DESTRUCTION ZONES FOR VARIOUS PESTICIDES
427-26-3	SUBMERGED-COMBUSTION INCINERATOR
427-26-4	KEPONE INCINERATION TEST SYSTEM
427-26-5	ROTARY KILN INCINERATOR
427-26-6	FLUIDIZED-BED INCINERATOR SCHEMATIC

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 27: NO_X CONTROL THEORY
427-27-1	SUMMARY OF 1974 STATIONARY SOURCE NO_X EMISSIONS
427-27-2	ANNUAL NATIONWIDE NO_X EMISSION PROJECTIONS TO 2000
427-27-3	EXAMPLE OF TRANSIENT SMOG CONDITIONS IN LOS ANGELES, CA
427-27-4	EXAMPLE OF EXPERIMENTAL SMOG CHAMBER DATA
427-27-5	GENERALIZED PHOTOCHEMICAL REACTIONS
427-27-6	GENERALIZED PHOTOCHEMICAL REACTIONS (CONTINUED)
427-27-7	THERMAL NO_X FORMATION: CLASSICAL CHEMICAL MODEL
427-27-8	THERMAL NO_X FORMATION: SIMPLIFIED MODEL
427-27-9	THEORETICAL CURVES FOR NO CONCENTRATIONS VS. TEMPERATURE
427-27-10	EFFECT OF LOW EXCESS AIR, OIL FUEL
427-27-11	TWO-STAGE COMBUSTION
427-27-12	TWO-STAGE COMBUSTION, OIL FUEL
427-27-13	EFFECT OF BURNER STOICHIOMETRY ON NO_X, COAL COMBUSTION
427-27-14	NO_X REDUCTION BY FLUE GAS RECIRCULATION
427-27-15	EFFECT OF FGR ON NO EMISSIONS
427-27-16	EFFECTS OF NO_X CONTROL METHODS
427-27-17	RANGE OF UNCONTROLLED UTILITY BOILER NO_X EMISSIONS
427-27-18	EFFECT OF FIRING METHOD, OIL FUEL
427-27-19	NO_X EMISSIONS WITH WATER INJECTION FOR NATURAL GAS-FIRED GAS TURBINE
427-27-20	EFFECT OF TEMPERATURE ON NO REDUCTION WITH AMMONIA INJECTION

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 28: IMPROVED PERFORMANCE BY COMBUSTION MODIFICATION
427-28-1	SMOKE-CO_2 PLOT FOR RESIDENTIAL OIL BURNERS
427-28-2	"LOWEST PRACTICAL CO_2", RESIDENTIAL BURNERS
427-28-3	EFFECT OF STACK TEMPERATURE AND CO_2 ON THERMAL EFFICIENCY
427-28-4	USUAL RANGE OF VISCOSITY FOR OIL FIRING
427-28-5	SMOKE-CO_2 CURVE FOR COMMERCIAL RESIDUAL OIL FIRED BURNER
427-28-6	MAXIMUM DESIRABLE BACHARACH SMOKE NUMBER
427-28-7	PERCENT CO_2 IN FLUE GAS AS FUNCTION OF EXCESS AIR
427-28-8	BOILER EFFICIENCY LOSS CHANGE WITH EXCESS O_2
427-28-9	SMOKE-O_2 CURVE FOR COAL OR OIL-FIRED INDUSTRIAL BOILER
427-28-10	CO-O_2 CURVE FOR GAS-FIRED INDUSTRIAL BOILER
427-28-11	EFFECT OF EXCESS O_2 ON NO_X EMISSIONS
427-28-12	TYPICAL RANGE OF MINIMUM EXCESS O_2 AT HIGH FIRING RATES
427-28-13	EFFECT OF REDUCING THE EXCESS AIR ON BOILER EFFICIENCY
427-28-14	STAGED AIR EXPERIMENTAL WATER TUBE BOILER, TOP VIEW
427-28-15	STAGED AIR EXPERIMENTAL WATER TUBE BOILER, SIDE VIEW
427-28-16	REDUCTION OF TOTAL NO_X BY STAGED AIR WITH NATURAL GAS FUEL
427-28-17	REDUCTION OF TOTAL NO_X BY STAGED AIR WITH NO. 6 FUEL OIL
427-28-18	EFFECT OF NO_X PORTS ON BOILER EFFICIENCY
427-28-19	EFFECT OF COMBUSTION AIR TEMPERATURE ON NO_X WITH OIL AND GAS
427-28-20	INFLUENCE OF AIR PREHEAT ON NO_X
427-28-21	EFFECT OF COMBUSTION AIR PREHEAT ON BOILER EFFICIENCY

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 28: IMPROVED PERFORMANCE BY COMBUSTION MODIFICATION, continued
427-28-22	REDUCTION IN NO_X BY FLUE GAS RECIRCULATION
427-28-23	NO_X FROM GAS, TANGENTIALLY-FIRED UTILITY BOILERS
427-28-24	EFFECTS OF NO_X CONTROL METHODS ON A GAS, WALL-FIRED UTILITY BOILER
427-28-25	EFFECT OF NO_X CONTROL METHODS ON AN OIL, WALL-FIRED UTILITY BOILER
427-28-26	NO_X FROM RESIDUAL OIL, TANGENTIALLY-FIRED UTILITY BOILERS
427-28-27	EFFECT OF BURNER STOICHIOMETRY ON NO_X IN TANGENTIAL, COAL-FIRED BOILERS

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 29: WASTE GAS FLARES
427-29-1	GAS PROPERTIES RE-FLARES
427-29-2	GAS PROPERTIES RE-FLARING
427-29-3	SMOKE TENDENCIES, ACETYLENE
427-29-4	SMOKE TENDENCIES, PROPANE
427-29-5	SMOKE TENDENCIES, ETHANE
427-29-6	SMOKE TENDENCIES, H/C $\geq$ 0.28
427-29-7	WATER-GAS REACTIONS
427-29-8	STEAM REQUIREMENTS FOR SMOKELESS FLARE
427-29-9	JOHN ZINK SMOKELESS FLARE TIP
427-29-10	CROSS SECTION OF A SMOKELESS FLARE BURNER
427-29-11	FLARE TIP WITH INTERNAL STEAM INJECTION
427-29-12	SINCLAIR FLARE BURNER
427-29-13	ESSO TYPE BURNER
427-29-14	MULTISTREAM-JET BURNER
427-29-15	MULTIJET-GROUND FLARE
427-29-16	VENTURI-TYPE FLARE
427-29-17	WATER SPRAY TYPE GROUND FLARE
427-29-18	NUMBER OF PILOTS REQUIRED

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 30: MUNICIPAL SEWAGE SLUDGE INCINERATION
427-30-1	TYPICAL SECTION OF A MULTIPLE-HEARTH SLUDGE INCINERATOR
427-30-2	MULTIPLE-HEARTH FURNACE FOR INCINERATING MUNICIPAL SEWAGE SLUDGE
427-30-3	SINGLE HEARTH SLUDGE FURNACE
427-30-4	FUNDAMENTALS OF FLUIDIZED INCINERATION

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Introduction to Combustion Evaluation in Air Pollution Control

COURSE: 427, Combustion Evaluation
LESSON TIME: 30 min.
PREPARED BY: J. T. Beard
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 1

Lesson Goal: The goal of this lesson is to familiarize the student with the goals and emphases of "Combustion Evaluation in Air Pollution Control."

Lesson Objectives: At the end of this lesson the student will be able to:

identify three major goals of Combustion Evaluation in Air Pollution Control;

list four of the subject areas which will be emphasized in the course (fundamentals of combustion, fuel properties, combustion system design, emission calculations, various combustion equipment topics, NO_X control);

present two reasons for applying the fundamental concepts of combustion when solving combustion evaluation problems in air pollution control;

list four of the materials burned as a fuel which are to be considered in the course;

list three waste materials which may be disposed of through combustion; and

list three of the important air pollutant emissions which may be limited by combustion control.

Student Prerequisite Skills: Air Pollution Training Institute Course 452 or equivalent experience, and one of the following: college level training in physical science, engineering, or mathematics.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 1.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 1.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 1: INTRODUCTION TO COMBUSTION EVALUATION IN AIR POLLUTION CONTROL
427-1-1	GOALS
427-1-2	COURSE WILL EMPHASIZE
427-1-3	FUEL BURNING SOURCES
427-1-4	COMBUSTION OF WASTE MATERIALS
427-1-5	AIR POLLUTION EMISSIONS CONTROLLED BY COMBUSTION
427-1-6	AT THE CONCLUSION OF THE COURSE

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Introduction to Combustion Evaluation

Page 4 of 5

NOTES

- I. Introduction
  - A. Introduce course moderator and lecturers
  - B. Discuss the jobs in control agencies and in industry where knowledge from this course would be useful
  - C. Present the procedures to be used in the course
    - 1. Refer students to the course agenda, student manual, and workbook
    - 2. Advise students on their mode of participation in the course
    - 3. Invite students to express their interest in certain subjects of the course
    - 4. Describe the method of taking the pre-test and post-test
    - 5. Emphasize the importance of completing the daily homework assignments
    - 6. Mention the criteria for awarding the course certificate and CEU's
  - D. Provide information about lunch and coffee breaks, transportation, restrooms, etc.
- II. Course Goals
  - A. Goals are to provide participants with knowledge of:

    Slide 427-1-1
    - 1. Fundamental aspects of combustion
    - 2. Applied aspects of combustion
    - 3. Overview of the state-of-the art
  - B. Basic concepts of combustion
    - 1. Definition and purpose of combustion
    - 2. Factors affecting completeness of combustion
      - a. Sufficient oxygen
      - b. Three T's of combustion
    - 3. Consequences of poor combustion
      - a. Smoke and other particulates
      - b. Carbon monoxide and other partially oxidized hydrocarbons
      - c. Odor
  - C. Give examples relating fundamental concepts to applied air pollution problems
    - 1. Fuel oil viscosity (which varies with temperature) influences droplet atomization size which could be too large for complete combustion in a given situation
    - 2. NO_x formation may be reduced by limiting the amount of excess air
  - D. State that emphasis will be placed on:
    - 1. Fundamental combustion calculations

      Slide 427-1-2
    - 2. Evaluation of pollution emissions
    - 3. Factors to consider for reduced emissions
      - a. Good equipment design
      - b. Proper installation
      - c. Good operating practices and maintenance program
    - 4. Corrective action for malfunctioning equipment

III. Distinguish between the content of this course and courses in gaseous and particulate emissions
   A. Course will emphasize commonly encountered
      1. Fuel combustion sources — Slide 427-1-3
         a. Major stationary sources burning natural gas
         b. Commercial, industrial, and utility sources burning fuel oil
         c. Industrial and utility sources burning coal
         d. Industrial sources burning wood (hog fuel)
         e. Special sources burning municipal solid waste
      2. Combustion devices for controlling waste gases
         a. Catalytic incineration
         b. Direct flame incineration
         c. Flares (as an optional topic)
      3. Combustible waste materials — Slide 427-1-4
         a. Various chemical and hazardous wastes
         b. Garbage (municipal solid wastes)
         c. Industrial waste gas streams containing combustible hydrocarbon and other gases
         d. Municipal sewage sludge (optional topic)
   B. Course will not emphasize flue gas control of:
      1. Particulates (covered in Course No. 412)
      2. Sulfur oxides (covered in Course No. 415)
   C. Air pollutants which can be reduced by properly controlled combustion are: — Slide 427-1-5
      1. Carbon monoxide
      2. Hydrocarbon gases
      3. Nitric oxides
      4. Combustible particulates resulting from incomplete oxidation
      5. Incombustible particulates resulting from entrainment by high-velocity gases

IV. Course Objectives
   A. Refer to list of objectives for each topic of the course (found in Chapter 1)
   B. Summarize the objectives for the participants — Slide 427-1-6
      1. Familiarity with combustion principles
      2. Ability to perform calculations to determine quantities of emissions and the requirements for complete combustion
      3. Ability to state important mechanisms in the formation of certain air pollution emissions
      4. Ability to understand and apply the important combustion design and operational parameters in order to make recommendations for improved air pollution control

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Fundamentals of Combustion I-
Basic Chemistry

COURSE: 427, Combustion Evaluation
LESSON TIME: 50 min.
PREPARED BY: L. U. Lilleleht
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 2

Lesson Goal: The goal of this lesson is to provide a review of the fundamental theory of chemical reactions as is related to combustion evaluation in air pollution control.

Lesson Objectives: At the end of this lesson the student will be able to:

use the basic chemical equations for combustion reactions, with or without excess air, to calculate air requirements and amounts of combustion products;

apply the ideal gas law to determine volumetric relationships for typical combustion situations;

distinguish between different types of combustion as characterized by carbonic theory (yellow flame) and hydroxylation theory (blue flame).

Student Prerequisite Skills: First-level college chemistry, algebra, physics (heat).

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 2.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 2.
2. Steam, Its Generation and Use, 38th Edition, published by Babcock and Wilcox Co., New York (1972).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 2: FUNDAMENTALS OF COMBUSTION II - BASIC CHEMISTRY
427-2-1	FUNDAMENTALS OF COMBUSTION
427-2-2	GENERAL COMBUSTION REACTION
427-2-3	THREE T'S OF COMBUSTION
427-2-4	COMPLETE COMBUSTION
427-2-5	THEORETICAL AIR FOR COMPLETE COMBUSTION
427-2-6	FLAMMABILITY LIMITS OF COMBUSTIBLE VAPORS IN AIR
427-2-7	STANDARD CONDITIONS
427-2-8	IDEAL (PERFECT) GAS LAW
427-2-9	CHARLES' AND BOYLE'S LAWS
427-2-10	SELECTED REACTIONS IN COMBUSTION SEQUENCE
427-2-11	CARBONIC THEORY
427-2-12	HYDROXYLATION THEORY
427-2-13	YELLOW FLAME
427-2-14	BLUE FLAME
427-2-15	STEAM INJECTION TO YELLOW FLAME

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Fundamentals of Combustion I- Basic Chemistry

Page 3 of 4

	NOTES
I. Introduction	
A. State the objectives of this lesson	Slide 427-2-1
B. Establish definitions and common terminology	
1. Combustion: rapid chemical reaction	
2. Balancing general oxidation reaction	Slide 427-2-2
a. Concept of mol	
b. Conversion from molar to mass or other bases	
3. Requirements for complete combustion	Slide 427-2-3
a. Oxygen	
b. Temperature, turbulence, time	
II. Determine the oxygen (air) requirements for combustion	
A. Theoretical (stoichiometric) air requirements and combustion products for	Refer to Student Manual, p.2-23
1. Single component combustibles	Slide 427-2-4
2. Mixtures of combustibles	427-2-5
B. Effects of insufficient air	
1. Carbon (smoke, soot)	
2. Carbon monoxide	
3. Partially oxidized hydrocarbons and odor	
C. Reasons for some excess air	
1. Complete combustion	
2. Temperature control in combustion zone	
D. Flammability characteristics of gases and vapors	
1. Combustion over range of concentration	Slide 427-2-6
a. Lower and upper flammability or explosive limits, homogeneous mixtures	
b. Effects of temperature and pressure on flammability limits	
2. Heterogeneous mixtures	
a. Multiphase (solid, liquid, gas) system	
b. Layered systems	
E. Volumetric relationships for gases and volumes	
1. Avogadro's law	
a. Equal volumes - equal number of molecules	
2. Standard conditions (T and p)	Slide 427-2-7
a. Universal scientific	
b. Gas industry	
c. Other	
3. Gas laws	Slide 427-2-8
a. Ideal (perfect) gas law	
Universal gas constant	
Consistent units	
b. Charles' law	Slide 427-2-9
c. Boyle's law	
d. Dalton's law	
III. The Three T's of Combustion	Slide 427-2-3
A. Temperature	
1. Ignition temperature	
a. For gases and vapors	
b. For coal	
2. Temperature accelerates reaction rate	

B. Turbulence
  1. Facilitates mixing of oxygen and fuel
  2. Break-up of boundary layers accelerates
    a. Vaporization of liquid fuel
    b. Removal of combustion products from surface of solid fuel particle
    c. Availability of oxygen to burning surface of solid particle
  3. Affects heat transfer in combustion chamber

C. Time
  1. Residence time for complete combustion
  2. Temperature effect
    a. Lower residence time at higher temperature
    b. Smaller size
  3. Residence time distribution
    a. Shape of furnace
    b. Flow pattern

IV. Combustion Mechanisms
  A. Sequence of reactions affected by — Slide 427-2-10
    1. Availability of oxygen
    2. Temperature, turbulence, and time
  B. Carbonic theory
    1. Yellow flame — Slide 427-2-11
  C. Hydroxylation theory — Slide 427-2-12
    1. Blue Flame
  D. Water-gas reaction to — Slide 427-2-13
    1. Mediate cracking reaction — Slide 427-2-14
    2. Control smoking tendency of flares — Slide 427-2-15

Summary

Knowledge of the fuel composition will permit the determination of the theoretical air requirements and the quantities and compositions of the flue products through the use of material balances.

Combustion is usually carried out at or near atmospheric pressures so that the use of the ideal gas law is justified for the relationship between the volume and the number of mols or mass of gases involved.

Temperature, time, and turbulence in a combustion device are important factors to be considered to assure complete combustion with a minimum of pollutant emissions.

Different theories have been proposed for the combustion mechanism. Which of these mechanisms is predominant depends on tye type of fuel and how it is mixed with air. The appearance of the flame can be used as an indication of the type of combustion and its quality.

Combustion calculations involving heat effects will be the subject of the next lecture.

LESSON PLAN

AIR POLLUTION
TRAINING INSTITUTE

TOPIC: Fundamentals of Combustion
II - Thermochemical
Relationships

COURSE: 427, Combustion Evaluation
LESSON TIME: 50 min.
PREPARED BY: L. U. Lilleleht
DATE: Aug. 1978

UNITED STATES · ENVIRONMENTAL PROTECTION AGENCY ·

Lesson Number: 3

Lesson Goal: The goal of this lesson is to provide a review of the fundamental theory of chemical reactions as is related to combustion evaluation in air pollution control.

Lesson Objectives: At the end of this lesson the student will be able to:

define heat of combustion, gross and net heating values, available heat, hypothetical available heat, sensible heat, latent heat, and heat content;

determine the available heat obtained from burning fuels at different flue gas exit temperatures and with various amounts of excess air, using generalized correlations;

perform heat content calculations for various flow streams in a combustion installation;

calculate furnace efficiency and describe the effects of varying air-to-fuel ratio on flue gas composition and furnace losses.

Student Prerequisite Skills: First-level college chemistry, algebra, physics (heat); Course 427, Lesson Number 2.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 3.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 2.

2. Combustion Handbook, 1st Edition, North American Manufacturing Company, Cleveland, OH (1952).

3. Air Pollution Engineering Manual, AP-40, 2nd Edition, pp. 176 and 935, USEPA (1973).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 3: FUNDAMENTALS OF COMBUSTION II - THERMOCHEMICAL RELATIONSHIPS
427-3-1	GROSS HEATING VALUE
427-3-2	NET HEATING VALUE
427-3-3	ADIABATIC STEADY STATE HEAT BALANCE
427-3-4	HEAT BALANCE ACROSS SYSTEM BOUNDARY WITHOUT HEAT LOSS
427-3-5	GENERALIZED COMPARISON OF PURE HYDROCARBON FUELS IN COMPLETE COMBUSTION
427-3-6	AVAILABLE HEATS FOR SOME TYPICAL FUELS
427-3-7	AVAILABLE HEATS WITH EXCESS AIR
427-3-8	FURNACE LOSSES
427-3-9	SUMMARY OF HEAT BALANCE TERMS

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Fundamentals of Combustion II-Thermochemical Relations

NOTES

I. Introduction and Definitions	
A. State the lesson objectives	Refer to Manual, Chapter 2
B. Sensible and latent heats	
C. Heat content or enthalpy	
D. Heat of reaction	
1. Standard heat of combustion	
2. Gross or higher heating value (HHV)	Slide 427-3-1
3. Net or lower heating value (LHV)	Slide 427-3-2
E. Available heat	Slide 427-3-3
F. Hypothetical available heat	
II. Heat Balance Calculations	
A. Concept of a heat balance	Slide 427-3-4
1. Terms included and their interrelations	
2. Determination of heat contents of various streams	
a. By calculations using heat capacities, etc.	
b. From tables	
3. System efficiency	
B. Determination of the available (useful) heat	
1. By calculation from heating values and heat contents of all streams	
a. Heating value of various fuels, e.g. Dulong formula	
b. Heat content of multicomponent gas streams	
2. Approximations of available heat	
a. For typical hydrocarbon fuels	Slide 427-3-5
b. For some specific fuels	Slide 427-3-6
c. Estimates for other fuels	
3. Available heat with excess air	Slide 427-3-7
a. As percent of gross heating value	
b. Excess air decreases maximum flue gas temperature	
4. Hypothetical available heat	
C. Furnace losses	Slide 427-3-8
1. Incomplete combustion losses	
2. Flue gas losses	
3. Radiation and wall losses	
4. Total losses are at a minimum	
a. With good mixing at stoichiometric air/fuel ratio	
b. With poor mixing at some excess air	
D. Adiabatic flame temperature	Slide 427-3-9
1. Definition	
2. Calculations and typical values	
a. With air as source of oxygen	
b. With pure oxygen	
3. Consequences of heat removal failure	

Summary

Thermochemical calculations are essential to determine the efficiency of a combustion process and the amount of fuel necessary to meet a specified load. They will also permit calculations of the auxiliary fuel requirements in installations where combustion is used for pollution abatement, as in afterburners.

The effect of the air-to-fuel ratio on the various heat losses was discussed. Minimizing flue losses due to incomplete combustion, excessive amounts of combustion air, and excessively high flue gas temperatures will not only conserve fuel, but will also help to alleviate the air pollution problem by reducing the stack emissions.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Film — "Three T's of Combustion"

COURSE: 427, Combustion Evaluation
LESSON TIME: 30 min.
PREPARED BY: L. U. Lilleleht
DATE: Sept. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 4

Lesson Goal: To reinforce the student's understanding of the fundamental combustion concepts, particularly as these relate to the design variables of combustion time, temperature, and turbulence.

Lesson Objectives: At the end of this film, the student will be able to:

list the chemical elements which combined with oxygen when fuels burn;

list the four items necessary for efficient combustion; and

describe qualitatively the interrelationships between time, temperature, turbulence, and oxygen required for proper combustion of a given fuel.

Student Prerequisite Skills: First-level college chemistry.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Film: "Three T's of Combustion"
2. 16 mm sound movie projector with a 12-inch-diameter take-up reel

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 2.

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Film — "Three T's of Combustion

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Page 2 of 2

NOTES

I. Introduction
   A. State the objective of the film.
   B. This movie shows how to obtain efficient burning without black smoke. Professor Miller starts out to define and discuss combustion, the Btu, and heats of combustion of various fuels. He then uses a modified kerosene lamp to illustrate the importance of sufficient oxygen, temperature, turbulence, and time for obtaining efficient combustion.
   C. Parts of a kerosene lamp are used in the demonstration: glass container for fuel, wick, grate, diffuser or tuyère, and lamp chimney.
   D. Conditions producing inefficient burning:
      1. No tuyère — lack of mixing (turbulence)
      2. No chimney — too much cool air (time and temperature)
      3. Cold chimney — low temperature in combustion zone
      4. Too much air — wasted heat
      5. Too little air — unburned fuel, smoke
   E. Methods to increase air and eliminate smoke:
      1. Taller chimney — increased draft
      2. Raise bottom of chimney — overfire air

II. "Three T's of Combustion"

Film: "Three T's of Combustion"

III. Discussion of comments and questions raised by viewers

IV. Summary of application of the 3T's to furnaces
   A. To complete combustion of any fuel, one needs:
      1. Sufficient oxygen
      2. Adequately high temperature
      3. Sufficient turbulence for mixing
      4. Sufficient time

      The effects of these factors are interrelated. For example, higher temperature and better mixing would permit completion of the combustion process in shorter time.
   B. To increase temperature:
      1. Preheat combustion air
      2. Insulate combustion chamber
      3. Design chamber to reflect heat inward
   C. To provide turbulence use:
      1. Air jets
      2. Baffles
   D. To provide adequate time:
      1. Properly designed combustion chamber
      2. Baffle design
      3. Reduced firing rate
   E. Items to check if there is a smokey flame:
      1. Too little air
      2. Too much air
      3. Inadequate mixing
      4. Cold furnace

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Reaction Kinetics

COURSE: 427, Combustion Evaluation
LESSON TIME: 50 min.
PREPARED BY: L. U. Lilleleht
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 5

Lesson Goal: To provide the student with an understanding of the influence of temperature and reactant gas concentrations on the equilibrium state and on the rates approaching that of equilibrium in combustion reactions.

Lesson Objectives: At the end of this lesson the student will be able to:

recite the conditions for equilibrium;

describe how an excess quantity of one reactant will affect other concentrations at equilibrium;

cite the expression for the rate of reaction;

identify the Arrhenius equation as a model for the influence of temperature on combustion rate;

define the activation energy;

describe the mechanism of catalytic activity; and

list the reasons for the deterioration of catalytic activity.

Student Prerequisite Skills: College chemistry and algebra, Course No. 427, Lesson Number 3.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 5.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 2.

2. Edwards, J. B., Combustion: The Formation and Emissions of Trace Species, Ann Arbor Science Publishers, Ann Arbor, Michigan (1974).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 5: REACTION KINETICS
427-5-1	CHEMICAL REACTION RATES
427-5-2	EQUILIBRIUM CONDITIONS
427-5-3	TRANSITION STATE CONCEPT
427-5-4	TEMPERATURE EFFECT ON REACTION RATE
427-5-5	TYPICAL CATALYSTS AND THEIR SUPPORTS
427-5-6	STEPS IN CATALYTIC REACTION SEQUENCE
427-5-7	SCHEMATIC OF THE CATALYTIC REACTION SEQUENCE
427-5-8	ARRHENIUS PLOT WITH AND WITHOUT CATALYST
427-5-9	DETERIORATION OF PLATINUM CATALYTIC ACTIVITY

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Reaction Kinetics

NOTES

- I. Introduction
  - A. State the lesson goal and objectives
  - B. Discuss general concepts of chemical reactions:
    - 1. Not as simple as equation implies
      - a. Often a sequence of steps
      - b. Intermediate steps not always shown
    - 2. Not always complete
      - a. Usually there is also a reverse reaction
    - 3. Law of mass action gives the rate of reaction as proportional to: — Slide 427-5-1
      - a. Concentrations of reactants
      - b. Coefficient of proportionality in the reaction velocity constant, k
- II. Chemical Equilibrium — Slide 427-5-2
  - A. Present the conditions of equilibrium
    - 1. No change in concentrations with time
    - 2. Forward and reverse reaction rates equal
  - B. Introduce the equilibrium constant, K
    - 1. Interrelation of concentrations
      - a. Excess of one reactant reduces concentration of the other
      - b. Rationale for excess air in combustion
- III. Reaction Mechanism — Transition State Theory
  - A. Describe how a reaction proceeds through an activated complex (Transition State)
  - B. Mention that reactants and products each have a distribution of energy states about some mean level
    - 1. For exothermic reactions, products are at lower mean level than reactants
    - 2. Difference in mean energy states is the heat of reaction (combustion)
    - 3. Spontaneous reactions do not occur for all exothermic cases at any temperature. Why not?
  - C. Discuss the transition state (activated complex) between reactants and products: — Slide 427-5-3
    - 1. At higher energy than either reactants or products
    - 2. Activation energy is the difference between energy of the transition state and the mean of the reactants
    - 3. Formed on collision of reactant having sufficiently high energies (equal to or exceeding that of the transition state)
      - a. Only a small fraction of molecules have such energies
      - b. This fraction increases with increasing temperature
    - 4. Activated complex is unstable, therefore, there are two options:
      - a. It breaks up to form products
      - b. It breaks up to give original reactants
  - D. Present reaction rate expressions
    - 1. Temperature effect through the velocity constant, k — Slide 427-5-4
    - 2. Arrhenius equation for k
      - a. Plot of log k vs. 1/T (Arrhenius plot)
      - b. Slope proportional to activation energy

IV. Reaction with catalysts	Refer also to Manual, Chap.13
A. Discuss the nature of catalytic activity	
1. Definition of a catalyst	Slide 427-5-5
a. Reaction occurs on catalyst surface	
b. Increased rate	
c. Amount produced and equilibrium unaffected	
2. Steps in surface-catalyzed reactions:	Slide 427-5-6
a. Diffusion to surface	
b. Adsorption of reactant(s)	
c. Reaction on surface	
d. Desorption of product(s)	
e. Diffusion to bulk	
B. Consider effect of a catalyst:	
1. Lower apparent activation energy	Slide 427-5-7
a. Lower slope of Arrhenius plot	
2. Comparison of reaction rates with and without catalysts	Slide 427-5-8
a. Catalyst gives same rate at lower temperature	
b. Catalyst gives higher rate at same temperature	
C. Describe the deterioration of catalytic activity from:	Slide 427-5-9
1. Poisoning	
a. Heavy metals	
b. Phosphates	
c. Arsenic compounds	
2. Suppressants	
a. Halogens	
b. Sulfur	
3. Fouling agents	
a. Alumina and silica dusts	
b. Iron oxides	
c. Silicones	
d. Carbon deposits and soot	
e. Dirt and grime	

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Fuel Properties

COURSE: 427, Combustion Evaluation
LESSON TIME: 40 min.
PREPARED BY: J. T. Beard
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 6

Lesson Goal: The goal of this lesson is to provide the student with an understanding of the various physical and chemical properties of fuels which influence pollutant emissions and are important for combustion system design and operation.

Lesson Objectives: At the end of this lesson the student will be able to:

state the important chemical properties which influence air pollutant emissions;

use the tables in the student manual to find representative values for given fuel properties;

describe the difference in physical features which limit the rate of combustion for gaseous, liquid, and solid fuels;

explain the importance of fuel properties such as flash point and upper and lower flammability limits which relate to safe operation of combustion installations;

use either specific or API gravity to determine the total heat of combustion of a fuel oil;

describe the influence of variations in fuel oil viscosity on droplet formation and on completeness of combustion and emissions;

list the important components in the proximate and ultimate analyses;

define "as fired," "as received," "moisture free," and "dry basis" as applied to chemical analyses of solid fuels; and

explain the significance of ash fusion temperature and caking index in the burning of coal.

Student Prerequisite Skills: First-level college chemistry, physics (heat).

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 6

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 3.
2. Fryling, G. R., Combustion Engineering, revised edition, published by Combustion Engineering, Inc., 277 Park Avenue, New York 10017 (1966).
3. Steam, Its Generation and Use, 38th Edition, published by Babcock and Wilcox, 161 East 42nd Street, New York 10017 (1972).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 6: FUEL PROPERTIES
427-6-1	GASEOUS FUELS HAVE RATE OF COMBUSTION
427-6-2	HIGHER HEATING VALUE
427-6-3	LOWER HEATING VALUE
427-6-4	API GRAVITY
427-6-5	APPROXIMATE VISCOSITY OF FUEL OIL
427-6-6	PROXIMATE ANALYSIS OF SELECTED COAL
427-6-7	ULTIMATE ANALYSIS OF SELECTED COAL (AS RECEIVED)
427-6-8	ULTIMATE ANALYSIS OF SELECTED COAL (DRY BASIS)
427-6-9	SELECTED SIZE DISTRIBUTION AND MOISTURE OF HOGGED FUELS

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Fuel Properties

NOTES

I. Introduction
  A. State the lesson objectives
  B. Describe the following fuel properties and introduce their influence on pollutant emissions
    1. Sulfur
      a. Present in organic, sulfide, or sulfate forms
      b. Give examples to show how sulfur content varies with fuel, source, and amount of cleaning or refinery processing
      c. Introduce acidic emissions which cuase corrosion in economizers, air heaters, and air ducts.
    2. Fixed nitrogen
      a. Give ranges of content in coal and oil
      b. Introduce fuel NO_x
      c. Explain why high nitrogen in natural gas does not form fuel NO_x
    3. Other impurities
      a. State examples: vanadium, sodium, and mercury
    4. Volatile matter, fixed carbon, ash
    5. Moisture
  C. Give examples of the most common solid, liquid, and gaseous fuels
    1. Gaseous fuels (natural gas, propane, butane)
    2. Liquid fuels (No. 2 fuel oil, No. 6 fuel oil)
    3. Solid fuels (coal, hogged fuel, municipal solid waste)
  D. Explain the limits on the rate of combustion
    1. Gaseous fuels limited by turbulence (mixing of fuel and air)

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    2. Liquid fuels limited by evaporation which is dependent on liquid surface area
    3. Solid fuels limited by distillation of volatiles and diffusion of O_2 to surface of fixed carbon
  E. Define, give example values for gas, oil, and coal, and explain the method used to determine

Slide 427-6-2

    1. Higher heating value, gross heat of combustion, gross calorific value, total heat of combustion
    2. Lower heating value, net heat of combustion

Slide 427-6-3

    3. Constant volume versus constant pressure values
  F. Review the upper and lower falmmability limits and discuss their application to avoid explosions
II. Gaseous Fuels
  A. Describe the characteristics of natural gas

Refer to Student Manual, p. 3-11

    1. Mixtures of gaseous components, mainly methane
    2. Higher heating value around 1,000 Btu/scf
    3. May contain sulfur when delivered from gas well, typically removed before transmission
    4. Usually contains trace mercaptan additive for odor detection of leaks
  B. Give example compositions and heating values for various synthetic gaseous fuels

1. Liquified Petroleum Gas, LPG
    a. Blend of paraffinic (saturated) hydrocarbons (propane, isobutane, and normal butane)
    b. Derived from natural gas and from petroleum refinery operations
    c. Gaseous under normal atmospheric conditions, but may be liquefied under moderate pressure (80-200 psig)
    d. Heating value (2,500 to 4,000 Btu/scf)
2. Gases derived from coal (metals or chemical industry) generally burned on site as heating fuel
    a. Coke-over gas
    b. Blast furnace gas
    c. Producer gas

Refer to Student Manual, p. 3-12

3. Synthetic gases from petroleum refineries
    a. Various blends of byproduct gases; heating value which depends on composition

III. Liquid Fuels
  A. Discuss crude oil
    1. Combustible hydrocarbon mixture as delivered from oil well
    2. Potential explosive problems when used as fuel, due to low flash point volatiles
    3. Used as refinery feed-stock to produce fuels, solvents, chemicals, plastics, synthetic rubber, etc.
  B. Describe the distinguishing characteristics of fuel oils of different grades

Refer to Student Manual, p. 3-13

    - No. 1 fuel oil, a distillate oil intended for vaporization pot-type burners and other burners requiring a light distillate fuel
    - No. 2 fuel oil, a heavier distillate oil typically used for domestic heating
    - No. 4 fuel oil, a light residual fuel for intermediate burners not equipped with preheating facilities
    - No. 5 fuel oil, a residual fuel oil which, depending on the blend and climate, may require heating prior to burning
    - No. 6 fuel oil (Bunker C), a heavy residual fuel which requires heating for both pumping and burning (atomization)
  C. Describe similarities of diesel and stationary gas turbine engine fuels
    1. Define, give examples, and state the air pollutant influence of
      a. Cetane number
      b. Distillation temperatures for different fractions
  D. Define, give example values, and describe the importance of the following fuel oil properties
    1. Specific gravity and API gravity
    2. Heating value
      a. Describe relationship to gravity

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Refer to Student Manual, p. 3-14

b. Use examples of a No. 6 fuel oil with specific gravity of .9861, containing 18,640 Btu/lb, and a No. 2 fuel oil with specific gravity of .8654, containing 19,490 Btu/lb

Refer to Student Manual, p. 3-15

3. Flash point
    a. Contrast with fire point (ignition temperature)
    b. Illustrate the concern about the explosion potential of a No. 2 fuel placed in the typical heated thank for No. 6 fuel oil
4. Viscosity

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    a. Explain the variation with temperature
    b. State that No. 5 and No. 6 fuel oils require heating for atomization and/or pumping
    c. Note that high viscosity at the burner causes large droplets to be formed. Incomplete combustion may occur (inadequate time for combustion, evaporation limited due to unfavorable area to volume)
5. Pour point
6. Fuel oil additives to be discussed in Lesson 18

IV. Solid Fuels
A. Coal is most abundant energy resource
1. Describe coal classification

Refer to Student Manual, p. 3-18, 3-19.
Slide 427-6-6
Slide 427-6-7

    a. Anthracite and bituminous coals classified according to fixed carbon
    b. Subbituminous and lignite coals classified according to heating value (generally)
2. Define and give example of ultimate analysis

Refer to Student Manual, p. 3-21

    a. Used in computing air requirements and pollutant emissions
3. Define and give example of proximate analysis
4. Contrast the definitions and uses of analyses which are on an "as received" (in the laboratory) basis with a "moisture free" or "dry" basis (without influence of moisture,which varies with handling and exposure conditions)
5. Define and describe the tests for surface moisture and for total moisture
6. Give example values for moisture, volatile matter, fixed carbon, sulfur, and ash contents

Refer to Student Manual, p. 3-20

    a. Eastern bituminous coal
    b. Western subbituminous coal
    c. Lignite
7. Describe and give examples of sulfur composition in coal
    a. Organic form, 30 to 70% of the sulfur
    b. Metal sulfide form (pyrite and marcasite), 40 to 80%
    c. Metal sulfate form (gypsum and barite), very small percentage
8. Describe the influence of coal cleaning on sulfur removal

9. State the distinguishing features of the following characteristics
    a. Ash softening temperature
       Initial deformation temperature
       Ash fusion temperature (fluid temperature)
    b. Free swelling index
    c. Caking coals (agglomerating index)
    d. Free burning coals
    e. Grindability index

B. State how coke is formed and provide examples of chemical analysis and heating value

C. Provide examples of the chemical and physical composition of wood and hogged fuel

D. Describe the source and the fuel properties of bagasse
   1. 40 to 60% moisture

E. Present the chemical and physical descriptions of the constituents of municipal solid waste
   1. Combustibles are mainly paper
   2. Moisture content around 20%, depending on weather exposure
   3. Noncombustibles and moisture may be removed to improve the heating value of the material

Refer to Student Manual p. 3-22
Slide 427-6-8
Slide 427-6-9
Refer to Student Manual, p. 3-23
Refer to Student Manual, p. 3-24, p. 3-25

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Problem Session I: Combustion Calculations

COURSE: 427, Combustion Evaluation
LESSON TIME: 70 min.
PREPARED BY: L. U. Lilleleht
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 7

Lesson Goal: To assure the student's ability to perform computations which make use of combustion fundamentals as applied to the determination of air requirements, flue gas characteristics, and heat available from burning a given fuel.

Lesson Objectives: At the end of this lesson the student will be able to:

determine the amount of air required for complete combustion of various fuels;

determine the heating values of various fuels and mixtures of combustibles;

determine the quantity and the composition (by weight and by volume) of flue gases;

calculate the enthalpy of gas streams at various temperatures;

perform heat balance calculations on combustion processes;

establish the quantity of heat available for some useful purpose as a function of flue gas exit temperature;

determine the thermal efficiency of a combustion process; and

estimate the effect of combustion air preheating on the thermal efficiency of the process.

Student Prerequisite Skills: First-level college chemistry, algebra, physics (heat); lessons 2, 3, 6.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Workbook for Combustion Evaluation in Air Pollution Control, Chapter I.
2. Blackboard and chalk or an overhead projector with transparency material and pens.
3. Hand-held calculator or slide rule.

Special Instructions: Assign problem I.5 for homework.

Reference: Combustion Evaluation in Air Pollution Control, Chapter 2.

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Problem Session I: Combustion Calculations

I. Introduction
A. State the goals and objectives of this lesson
B. Goals are to be achieved by:
1. Instructor working through and discussing Problem I.1 and Problem I.3.
2. Students working problems independently
a. In class: Problem I.2 and I.4
b. Homework assignment: Problem I.5
3. Discussion of solutions of problems

II. Problem I.1: Combustion of No. 6 Fuel Oil
A. Present the problem statement:
Assume perfect combustion of No. 6 fuel oil with stoichiometric air.
Predict:
1. The gravimetric analysis (weight percent) of the flue gases
2. Total volume of flue gases (at 500°F and 1 atmosphere) per pound of oil burned
3. Volume percent of CO_2 in dry flue gases
B. Present, as given: the gravimetric analysis of this fuel oil:

88.52%	carbon
10.87%	hydrogen
0.40%	sulfur
0.10%	nitrogen
0.06%	oxygen
0.05%	ash

C. Decide on basis for calculations — unit mass
D. Determine the mass of gaseous combustion products from the ultimate analysis
E. Calculate the volume of:
1. Individual combustion products
2. Total volume
a. At standard conditions
b. At actual conditions
3. Dry flue gas volume at standard conditions
F. Determine the ultimate percent CO_2
G. Discuss the significance of these results
H. Outline how similar calculations could be performed for gaseous and solid fuels

III. Problem I.2: Combustion of Gases
A. Present the problem statement:
Consider a gaseous fuel composed of 60% H_2 and 40% CH_4 by volume
Determine:
1. The volume of air required for complete combustion of 1,000 scfm of the above gases with 100% theoretical air.
2. The pounds of air required for burning 1.00 pounds of fuel.
3. The volumetric analysis of flue gases (products), including water vapor (assume no water is condensed).

NOTES

Refer to Student Manual, p. 2-23, Attachment 2-1.

Refer to perfect gas law in Student Manual, p. 2-24.

Compare with value obtained using Student Manual, p. 2-30.

4. The gravimetric analysis of the reactants (fuel gas and air mixture).
5. The partial pressure of the water vapor in the flue for a total pressure of 14.7 psia.

B. Solution is to be computed by students during class
C. Present and discuss solution

IV. Problem I.3: Available Heat

A. Present the problem statement:
Consider a boiler which burns 10,000 standard cubic feet per hour of a waste gas with higher heating value of 258 Btu/scf.

Determine:

1. The gross heating value per hour for complete combustion.
2. The available heat if the flue gases leave the boiler heat exchanger at 500°F and complete combustion is achieved with theoretical combustion air.
3. The available heat from the same boiler if 20% excess air had been used and flue gas exit temperature was still 500°F.

B. Choose a basis for calculations — unit time.
C. Determine the gross heating value.
D. Illustrate the use of Attachment 2-9
E. Discuss effect of excess air
F. Outline how more accurate estimate of available heat could be obtained from heat balance calculations based on enthalpies of all streams and heating value of the fuel

Refer to Student Manual, p. 2-31, p. 2-32, p. 2-28.

V. Problem I.4: Liquid Waste Combustion in Natural Gas-Fired Boiler

A. Present the problem statement:
Combustible liquid waste from a manufacturing process is to be burned in a boiler which is fired with 1,059 Btu/scf higher heating value natural gas at a rate of 5,000 scfh. The liquid waste is equivalent to 10 lb/h of benzene.

Determine:

1. The total gross heating value to the boiler per hour.
2. The amount of combustion air required to burn the waste liquid. Assume a 20% excess of theoretical air and express your results in scfm.
3. The amount of available heat from the boiler if the flue gases leave the heat exchanger at 600°F and complete combustion is achieved with 20% excess air.

B. Present the flow diagram
C. Solution by Students
D. Discuss solution

1. Gross heating value: sum of HHV for gas and waste.
2. Air requirement
   a. Theoretical for gas and waste
   b. Add 20% for excess air
3. Available heat

Refer to Student Manual, p. 2-23.

Refer to Student Manual, p. 2-32.

VI. Problem I.5: Combustion Calculations with Heat Recovery

- A. Assign this problem for homework
- B. Discuss flow diagram.
- C. Review problem statement:

A chemical plant has installed an industrial boiler to produce process steam. The boiler is fired with natural gas of the following composition by volume: 90% methane, 5% ethane, and 5% nitrogen. The boiler is designed to burn 80,000 cubic feet per hour (delivered at 60°F) of natural gas at 10% excess combustion air.

Determine:

1. The gross heat input to the boiler, BTU per hour. (Assumptions: (a) Natural gas and combustion air enter the boiler at 60°F; (b) heat losses from the boiler due to radiation and convection are negligible.)
2. The combustion air requirement, cubic feet per hour (at 60°F, 30 inches mercury pressure). Assume average atmospheric conditions are 60°F and 30 inches mercury pressure.
3. The available heat for process steam if the flue gases leave the boiler heat exchanger at 400°F.

The personnel of the chemical plant are now considering the addition of an air preheater to the boiler to preheat combustion air. Calculations show that the flue gases leaving the heat exchanger section would enter the air preheater at the following conditions: 1,500,000 cubic feet per hour at 400°F. The air preheater will be designed to reduce the flue gas temperature to 350°F. At conditions of complete combustion, calculations show the flue gases entering the air preheater to be of the following composition by volume: 8.8% CO_2, 1.7% O_2, 72.3% N_2, and 17.2% H_2O. (Note: Calculations show the water vapor flow rate in the flue gases equals 7,400 lbs. per hour.)

Determine:

4. The heat recovered (H.R.) from the flue gases by the air preheater based on the flue gas analysis and flue gas flow rate. (Note: Use Equation 1 shown below.)
5. The increase in combustion air temperature resulting from the use of an air preheater. (Note: Use Equation 2 shown below.)
6. The combustion air temperature after passing through the air preheater.

$$\text{H.R.} = \sum \text{(flow rate of each component)} \times \text{(difference in heat content of each)} \qquad (1)$$

$$\text{H.R.}_{\text{Air}} = 0.24\ \frac{\text{Btu}}{\text{lb}^{\circ}\text{F}} \times \text{temperature increase} \times \text{air flow rate} \qquad (2)$$

CHAPTER I

COMBUSTION CALCULATIONS

PROBLEM I.1: Combustion of No. 6 Fuel Oil

Assume perfect combustion of No. 6 fuel oil with stoichiometric air. The gravimetric analysis of a sample of this fuel oil is:

88.52%	carbon
10.87%	hydrogen
0.40%	sulfur
0.10%	nitrogen
0.06%	oxygen
0.05%	ash

Compute:

1. The gravimetric analysis (weight percent) of the flue gases
2. Total volume of flue gases (at 500°F and 1 atmosphere) per pound of oil burned
3. Volume percent of CO_2 in dry flue gases

Solution to Problem I.1:

Select as a basis for calculation: 100 lbs. of fuel oil burned. This is chosen for convenience as the gravimetric analysis will give the amounts of various elements directly. Answers can easily be scaled to the 1 lb. of oil as required in Part 2.

A tabular form of solution is presented on the next page, as this will (i) help to organize thinking, (ii) permit presentation of results in a compact format, and (iii) avoid confusion

TABLE I.1

FUEL				COMB. AIR REQ'D		FLUE PRODUCTS				
Element (a)	M.W. (b)	Quantity lb. (c)	Quantity lb-mole (d)	O_2 lb-mole (e)	N_2 lb-mole (f)	Cmpd. (g)	M.W. (h)	lb-mole (i)	lb. (j)	wgt % (k)
C	12	88.52	7.38	7.38	27.8	CO_2	44	7.38	325	21.8
H_2	2	10.87	5.44	2.72	10.2	H_2O	18	5.44	97.9	6.6
S	32	0.40	0.012	0.012	0.045	SO_2	64	0.012	0.77	0.05
O_2	32	0.06	0.002	-0.002	-0.007	O_2	32	-	-	-
N_2	28	0.10	0.0036	-	-	N_2	28	38.0	1064	71.5
Ash	-	0.05	-							
Total		100.00		$\underbrace{10.11 \quad 38.04}_{48.15}$				50.8	1,488	99.95

Notes for Column Headings:

(c) From gravimetric analysis of fuel

(d) = (b) x (c)

(e) From basic chemistry, i.e.:

$$C + O_2 \rightarrow CO_2$$
$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$
$$S + O_2 \rightarrow SO_2$$

Oxygen in fuel reduces air requirements. Excess air, if any, is usually specified as % of theoretical and added to the total.

(f) = (0.79/0.21) x (e)

(g) Products corresponding to complete combustion of various oxidizable elements in the fuel

(i) Pound-moles of products from the amount of combustibles in (d). Note that oxygen present only if excess air added, and nitrogen is the total of (f), including any from excess air.

(j) = (h) x (i)

(k) = (j) x $100/\Sigma(j)$

Part 1.

Gravimetric analysis of flue gases given by Column (k) of the table.

Part 2.

Ideal gas law used to calculate the volume of flue gases (Equation 2.6, p. 2-8 of the Student Manual).

$$V = nRT/p$$

where $n = \dfrac{50.8 \text{ lb-moles flue gases}}{100 \text{ lb oil}} = 0.508 \text{ lb-moles/lb}$

from Table I.1

$R = 0.7302 \text{ atm-ft}^3/(\text{lb-mole } {}^\circ\text{R})$

from Attachment 2-2, p. 2-24 of the Student Manual

$T = 500^\circ\text{F} + 460 = 960^\circ\text{R}$

$P = 1.0$ atm.

$$V = (0.508)\ (0.7302)\ (906)/(1.0) = \underline{\underline{356 \text{ ft}^3}}$$

Part 3.

Dry flue gases (from Table I.1)

Compound	lb-moles
CO_2	7.38
SO_2	0.012
O_2	-
N_2	38.0
Total	45.4 lb-moles

$$\text{Vol. \% } CO_2 = 7.38 \times 100 / 45.4 = \underline{\underline{16.3\ \%}}$$

(I-3)

PROBLEM I.2: Combustion of Gases

Consider a gaseous fuel composed of 60% H_2 and 40% CH_4 by volume.

Determine:

1. The volume of air required for complete combustion of 1,000 scfm of the above gases with 100% theoretical air
2. The pounds of air required for burning 1.00 pounds of fuel
3. The volumetric analysis of flue gases (products), including water vapor (assume no water is condensed)
4. The gravimetric analysis of the reactants (fuel gas and air mixture)
5. The partial pressure of the water vapor in the flue for a total pressure of 14.7 psia

Solution to Problem I.2:

Complete and balance the combustion equation using 1 lb-mole of gas as the basis.

$$0.60\ H_2 + 0.40\ CH_4 + a\ O_2 + b\ N_2 \rightarrow c\ CO_2 + d\ H_2O + b\ N_2 \qquad (A)$$

To balance the equation

$$c = \underline{0.40}$$

$$d = 0.60 + 2\ (0.40) = \underline{1.40}$$

$$a = c + d/2 = \underline{1.10}$$

$$b = (0.79/0.21)\ a = \underline{4.14}$$

Thus:

$$0.60\ H_2 + 0.40\ CH_4 + \underline{1.10}\ O_2 + \underline{4.14}\ N_2 \rightarrow \underline{0.40}\ CO_2 + \underline{1.40}\ H_2O + \underline{4.14}\ N_2 \qquad (B)$$

Rel. Volumes:

$$\underbrace{0.60 + 0.40}_{1.00} + \underbrace{\underline{1.10} + 4.14}_{5.25} \rightarrow \underline{0.40} + \underline{1.40} + 4.14 \qquad (C)$$

$$\text{Rel. Mass:}\quad \underbrace{1.20 + 6.40}_{7.60} + \underbrace{\underline{35.2} + 115.9}_{\underline{151.1}} \rightarrow \underline{17.6} + \underline{25.2} + 115.9 \qquad \text{(D)}$$

Part 1.

From Equation (C) note that 5.24 volumes of air required for complete combustion of 1.00 volumes of this fuel gas.

Therefore:

$$\text{Vol. of air} = (5.24 \text{ scfm air/scfm gas})\ (\underline{1{,}000} \text{ scfm gas}) = \underline{5{,}240} \text{ scfm air}$$

Another approach makes use of Equation 2.4, p. 2-7 of the Student Manual, which for gases containing only H_2 and CH_4 reduces to:

$$V_{A,\,t} = 2.38\,(H_2) + 9.53\,(CH_4) \qquad \text{(E)}$$

where $(H_2) = 0.40$

$(CH_4) = 0.60$

$$V_{A,\,t} = 2.38\,(\underline{0.40}) + 9.53\,(\underline{0.60}) = 5.24 \text{ scf air/ scf gas}$$

which is the same as obtained in the Preliminary Calculation (Equation C above).

Part 2.

From Equation D above, 7.60 lb. of fuel gas requires 151.1 lb. air.

$$\text{Air required per pound of gas burned} = (\underline{151.1} \text{ lb. air})/7.60 \text{ lb. gas}$$

$$= \underline{19.9} \text{ lb. air/lb. gas}$$

Part 3.

From Equation (C) above, total volume of flue products is:

$$\underset{CO_2}{\underline{0.40}} + \underset{H_2O}{\underline{1.40}} + \underset{N_2}{4.14} = \underline{5.94}$$

Volume % of flue products:

% CO_2 = $\underline{0.40}$ x 100 / (Result of Equation F above) = $\underline{6.7}$ %

% H_2O = $\underline{1.40}$ x 100 / $\underline{(5.94)}$ = $\underline{23.6}$ %

% N_2 = 4.14 x 100 / $\underline{(5.94)}$ = $\underline{69.7}$ %

Part 4.

Tabulate the left-hand side of Equation (B) above:

Reactant	Relative Mass	Wgt. %
H_2	1.20	0.76
CH_4	6.40	4.03
O_2	35.2	22.18
N_2	115.9	73.03
Total	158.7	100.0

Note: Wgt. % of Reactant i = (Mass of i) x 100 / Total Mass

Part 5.

Partial pressure of a gaseous component is given by Equation 2.9, p. 2-10 of the Student Manual.

$$p_{H_2O} = (n_{H_2O}) \times (p)/n_{total} \tag{G}$$

where n = lb-moles or volume from Equation (C)

p = total pressure of flue products

Thus:

p_{H_2O} = (1.40 lb-moles H_2O) (14.7 psia) / (5.94 lb-moles of flue gases)

p_{H_2O} = 3.46 psia

PROBLEM I.3: Available Heat

Consider a boiler which burns 10,000 standard cubic feet per hour of a waste gas with higher heating value of 258 Btu/scf.

Determine:

1. The gross heating value per hour for complete combustion
2. The available heat if the flue gases leave the boiler heat exchanger at 500°F and complete combustion is achieved with theoretical combustion air
3. The available heat from the same boiler if 20% excess air had been used and flue gas exit temperature was still 500°F

Solution to Problem I.3:

Part 1.

Gross heating value per hour = (Q_H, Btu/scf) (Fuel rate, scf/hr) (A)

= (258 Btu/scf) (10,000 scf/hr)

= 2,580,000 Btu/hr

Part 2.

Use Attachment 2-9, p. 2-31 of the Student Manual to estimate the available heat, Q_A, from the above fuel with flue gases at 500°F.

Interpolate between curves in Attachment 2-9 at identical flue gas temperatures using the following ratio:

$$\left[\frac{Q_A}{Q_H}\right]_{\text{Desired fuel}} = \left[\frac{Q_A}{Q_H}\right]_{\text{Reference fuel}} \qquad \text{(B)}$$

Choosing Producer Gas as the reference fuel:

$$(Q_A/Q_H)_{\text{Ref. fuel, }500^\circ\text{F}} = (130/163) = 0.80$$

With waste gas: Q_H = 258 Btu/scf, from Equation (B) above:

$$Q_A = (258 \text{ Btu/scf})\ (0.80) = 206 \text{ Btu/scf}$$

Total heat available from waste gases = (10,000 scfh) (206 Btu/scf)

= 2,060,000 Btu/hr

Part 3.

Attachment 2-10, p. 2-32 of the Student Manual, gives available heat as the percent gross heating value with various amounts of excess air.

With flue gases at 500°F and 20% excess air, read

$$(Q_A/Q_H) \times 100 = 79\% \qquad \text{(C)}$$

Thus, heat available per hour with 20% excess air is:

$$Q_A = (79/100)\ (2{,}580{,}000 \text{ Btu/hr}) = 2{,}038{,}000 \text{ Btu/hr}$$

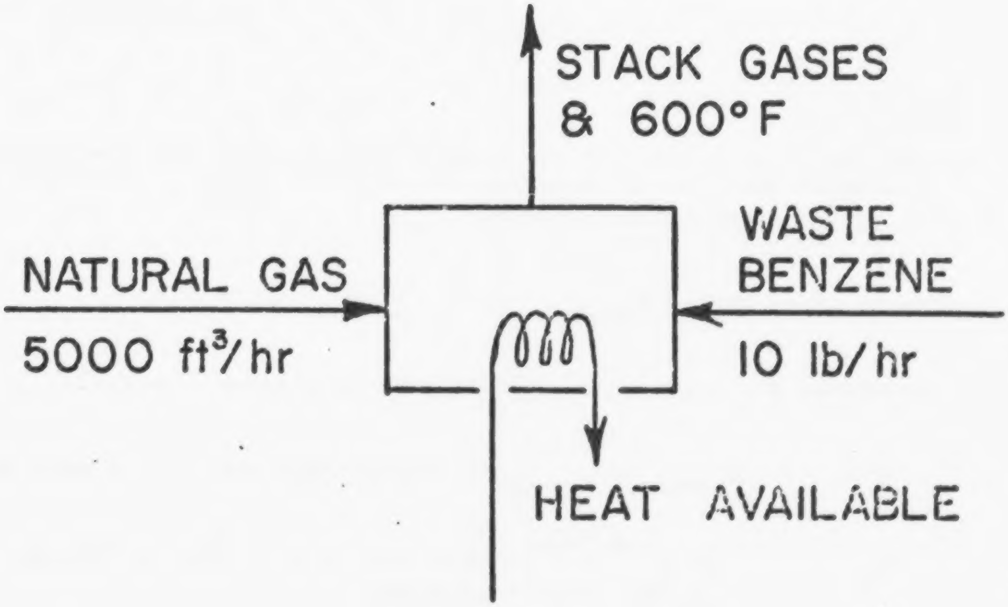
PROBLEM I.4: Liquid Waste Combustion in Natural Gas-Fired Boiler

Combustible liquid waste from a manufacturing process is to be burned in a boiler which is fired with 1,059 Btu/scf higher heating value natural gas at a rate of 5,000 scfh. The liquid waste is equivalent to 10 lb/h of benzene.

Determine:

1. The total gross heating value to the boiler per hour.
2. The amount of combustion air required to burn the waste liquid. Assume a 20% excess of theoretical air and express your results in scfm.
3. The amount of available heat from the boiler if the flue gases leave the heat exchanger at 600°F and complete combustion is achieved with 20% excess air.

Flow Diagram


STACK GASES
& 600°F
NATURAL GAS
5000 ft³/hr
WASTE
BENZENE
10 lb/hr
HEAT AVAILABLE

Solution to Problem I.4:

Choose as a basis:

1 hour of operation.

Part 1.

Gross heating value of natural gas: $Q_{H,\ gas} = 1{,}059$ Btu/scf.

Gross heating value of benzene is obtained from Attachment 2-1, p. 2-23 of the Student Manual:

$Q_{H,\ benzene} = \underline{18{,}184}$ Btu/lb

Total gross heat input to the boiler is:

Natural gas (5,000 scfh) (1,059 Btu/scf) = 5,295,000 Btu/hr

Benzene (10 lb/hr) (18,184 Btu/lb) = 181,840 Btu/hr

Total = 5,477,000 Btu/hr

Part 2.

Attachment 2-1, p. 2-23 of the Student Manual, gives the combustion air requirement for benzene (Substance No. 21) as 13.30 lb air/lb benzene or 35.73 scf air/scf benzene.

Density of benzene; $\rho_{benzene}$ is 0.2060 lb/scf.

Theoretical air required to burn benzene type waste completely

$$V_{A,\ t} = (\dot{m}_{benzene}/\rho_{benzene})\ \text{(Theoretical scf air/scf benzene)}$$

$$V_{A,\ t} = \frac{10\ \text{lb/hr}}{(\underline{0.2060}\ \text{lb/scf benzene})} \times \underline{35.73}\ \text{scf air/scf benzene)}$$

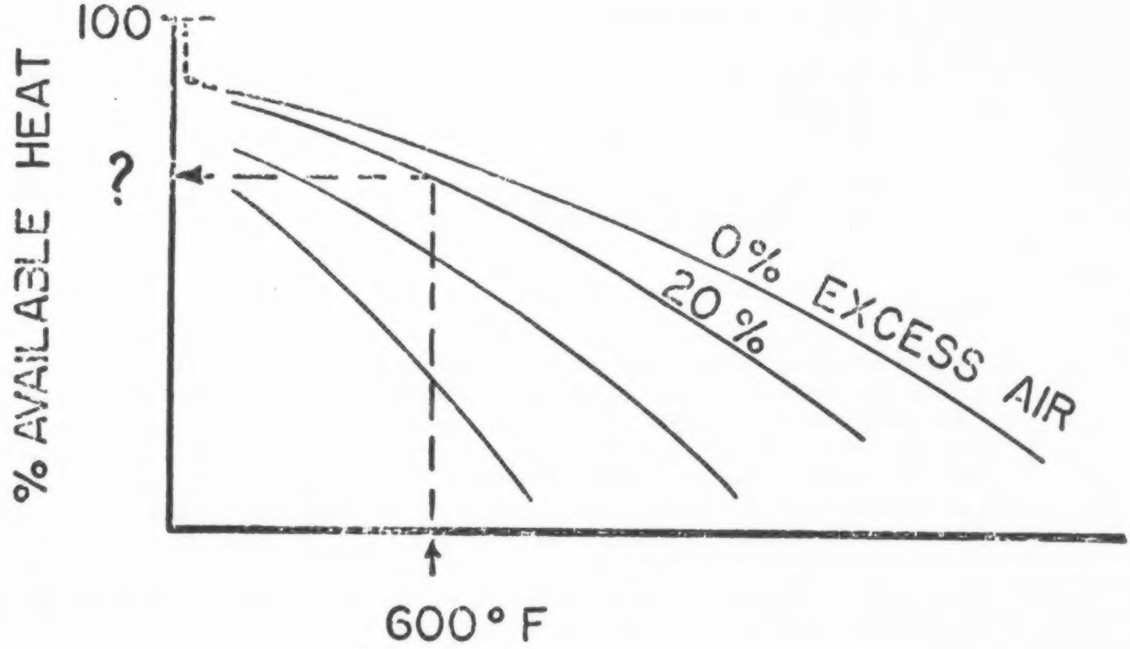
$$= \underline{1{,}730}\ \text{scf air/hr}$$

Air requirements with 20% excess air:

V_{air} = (1.20) (1,730 scf air/hr) = 2,080 scf air/hr

Part 3.

Refer to Attachment 2-10, p. 2-32 of the Student Manual. Read available heat as percent of gross heating value with flue gases at 600°F and 20% excess air as 77 %



Heat available from the boiler

= (5,477,000 Btu/hr) (77 %/100) = 4,220,000 Btu/hr

[from Part 1] [from Attachment 2-10]

PROBLEM I.5: Combustion Calculations with Heat Recovery

Part A

A chemical plant has installed an industrial boiler to produce process steam. The boiler is fired with natural gas of the following composition by volume: 90% methane, 5% ethane, and 5% nitrogen. The boiler is designed to burn 80,000 cubic feet per hour (delivered at 60°F) of natural gas at 10% excess combustion air.

Determine:

1. The gross heat input to the boiler, Btu per hour. Assumptions: (a) natural gas and combustion air enter the boiler at 60°F; (b) heat losses from the boiler due to radiation and convection are negligible.

2. The combustion air requirement, cubic feet per hour (at 60°F, 30 inches mercury pressure). Assume average atmospheric conditions are 60°F and 30 inches mercury pressure.

3. The available heat for process steam if the flue gases leave the boiler heat exchanger at 400°F.

Part B

The personnel of the chemical plant are now considering the addition of an air preheater to the boiler to preheat combustion air. Calculations show that the flue gases leaving the heat exchanger section would enter the air preheater at the following conditions: 1,500,000 cubic feet per hour at 400°F. The air preheater will be designed to reduce the flue gas temperature to 350°F. At conditions of complete combustion, calculations show the flue gases entering the air preheater to be of the following composition by volume: 8.8% CO_2, 1.7% O_2, 72.3% N_2, and 17.2% H_2O. (Note: Calculations show the water vapor flow rate in the flue gases equals 7,400 lbs. per hour.)

Determine:

4. The heat recovered (H.R.) from the flue gases by the air preheater based on the flue gas analysis and flue gas flow rate. (Note: Use Equation 1 shown below.)

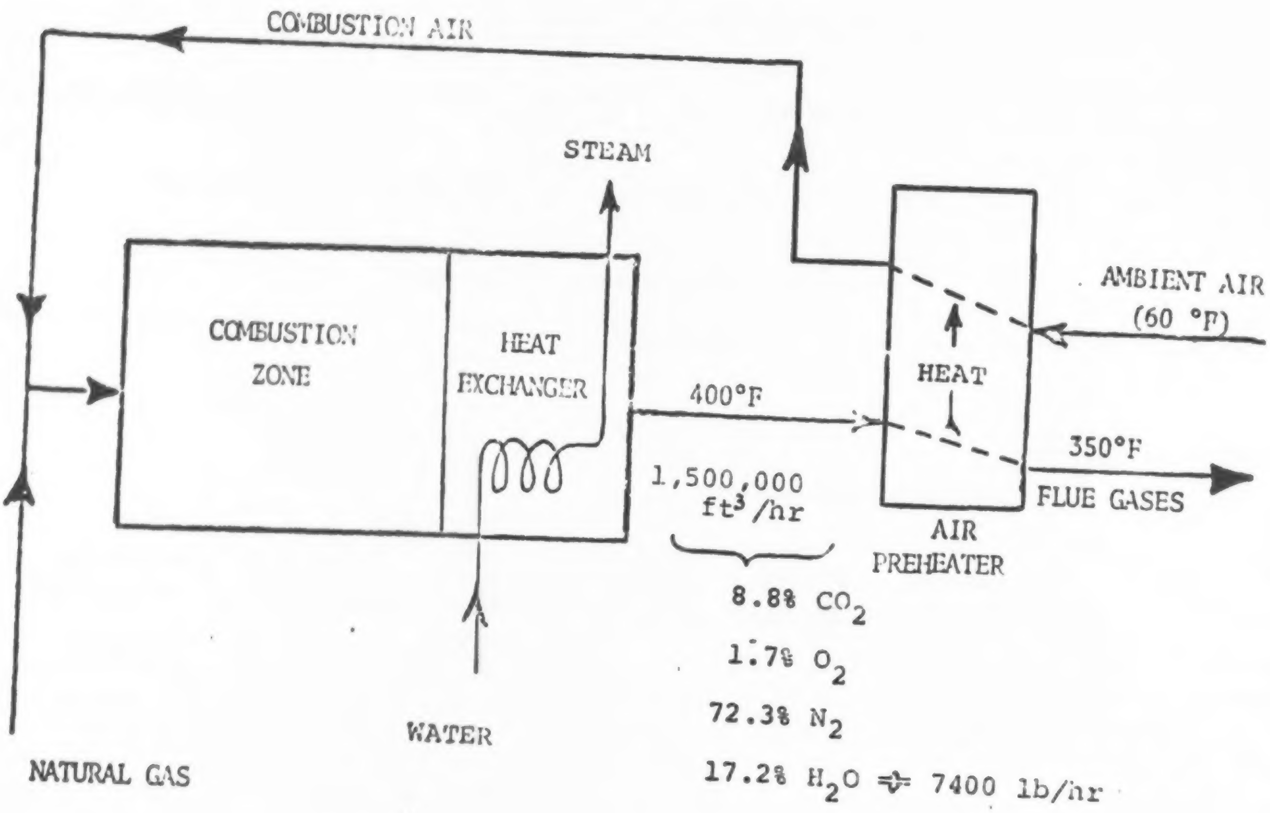
5. The increase in combustion air temperature resulting from the use of an air preheater. (Note: Use Equation 2 shown below.)

6. The combustion air temperature after passing through the air preheater.

$$\text{H.R.} = \sum \text{(flow rate of each component)} \times \text{(difference in heat content of each)} \quad (1)$$

$$\text{H.R.}_{\text{Air}} = 0.24 \frac{\text{Btu}}{\text{lb } ^{\circ}\text{F}} \times \text{temperature increase} \times \text{air flow rate} \quad (2)$$

FLOW DIAGRAM FOR BOILER:



COMBUSTION AIR
STEAM
COMBUSTION ZONE
HEAT EXCHANGER
HEAT
AIR PREHEATER
AMBIENT AIR (60 °F)
400°F
350°F
FLUE GASES
1,500,000 ft³/hr
8.8% CO2
1.7% O2
72.3% N2
17.2% H2O ⇒ 7400 lb/hr
WATER
NATURAL GAS

Solution to Problem I.5:

Basis: 1 hour of operation

Part 1.

Substance		Volumetric Flow Rate scfh	(a) Gross Htg. Value, Btu/scf	(b) Heat Input Btu/hr
Methane — CH_4	(0.90)(80,000) =	72,000 ;	1,012	72,860,000
Ethane — C_2H_6	(0.05)(80,000) =	4,000 ;	1,773	7,090,000
Nitrogen — N_2	(0.05)(80,000) =	4,000 ;	0	0
	Totals:	80,000 scfh		79,950,000 Btu/hr

Note: (a) From Attachment 2-1, p. 2-23 of the Student Manual.

(b) Obtained by multiplying volumetric flow rate by the corresponding gross heating value.

Part 2.

Combustion air requirements:

Combustible Substance	Volume, scfh	Theor. Air* scf air/scf gas	Actual Air (10% excess) scf air/scf	scf air/hr
CH_4	72,000	9.53	10.48	755,000
C_2H_4	4,000	16.68	18.35	73,000

Total Air = 828,000 scfh

*From Attachment 2-1, p. 2-23 of the Student Manual.

Part 3.

For available heat as percent of gross heating value, use Attachment 2-10, p. 2-23 of the Student Manual.

Read for 400°F flue gases and 10% excess air 83 %.

Available heat from the boiler = (79,950,000 gross Btu/hr)(83 % gross/100)

= 66,400,000 Btu/hr.

Part 4.

Need to calculate flow rate of combustion products in lb/hr. First correct flue gas flow rate from 400°F to standard temperature of 60°F, using Charles' law (Equation 2.7, p. 2-9 of the Student Manual).

$$V_{\text{flue, }60^\circ F} = (1{,}500{,}000\ \text{ft}^3/\text{hr})\ (460 + 60\ ^\circ F)\ /\ (460 + 400\ ^\circ F)$$

$$= 907{,}000\ \text{ft}^3/\text{hr}$$

Mass flow rate of component = (volume fraction) (total volume flow) (density)

Component	Fraction	Density lb/ft^3	Mass Flow lb/hr	Enthalpy, Btu/lb			
				at 400°F		at 350°F	
				Btu/lb	Btu/hr	Btu/lb	Btu/hr
CO_2	0.088	0.1170	9,340	75.3	0.703×10^6	63.7	0.594×10^6
O_2	0.017	0.0846	1,300	76.2	0.099×10^6	64.8	0.084×10^6
N_2	0.723	0.0744	48,790	85.0	4.147×10^6	72.4	3.53×10^6
H_2O	-	-	7,400	1,212	8.97×10^6	1,188	8.79×10^6
Total	1.00		66,830	H_{400}	$= 13.92 \times 10^6$	H_{350}	$= 13.00 \times 10^6$

Note: Densities available from Attachment 2-1, p. 2-23 of the Student Manual. Enthalpies from Attachment 2-7, p. 2-29 of the Student Manual.

Heat recovered from cooling flue gases = $(H_{400} - H_{350})$ Btu/hr.

$$\text{H.R.}_{\text{Air}} = \Delta H_{\text{Flue Gases}} = \underline{13.92 \times 10^6} - \underline{13.00 \times 10^6} = \underline{920{,}000} \text{ Btu/hr}$$

Part 5.

Refer to Equation (2) of the Problem Statement, which on rearrangement gives:

$$\Delta T_{\text{Air}} = (\text{H.R.}_{\text{Air}}) / (0.24 \text{ Btu lb}^{\circ}\text{F} \times \text{Air Flow Rate, lb/hr})$$

Obtain density of air from Attachment 2-1, p. 2-23 of the Student Manual, to compute:

Air Flow Rate, lb/hr = (Volumetric Air Flow, scfh)(density, lb/scf)

= (828,000 scfh)(0.0766 lb/scf)

= 63,400 lb/hr.

Substituting into expression for ΔT_{Air} :

$$\Delta T_{\text{Air}} = \frac{(\underline{920{,}000} \text{ Btu/hr})}{(0.24 \text{ Btu/lb-}^{\circ}\text{F}) (\underline{63{,}400} \text{ lb/hr})} = \underline{60.4}\ ^{\circ}\text{F}$$

Part 6.

Air temperature after preheater = $60^{\circ}\text{F} + \Delta T_{\text{Air}}$

$= 60 + \underline{60} = \underline{120}\ ^{\circ}\text{F}$

LESSON PLAN

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

TOPIC: Review of Homework

COURSE: 427, Combustion Evaluation
LESSON TIME: 30 min. (Tues.) and
15 min. (Wed., Thurs., Fri.)
PREPARED BY: J. T. Beard
DATE: Oct. 1978

Lesson Number: 8

Lesson Goal: The goal of this lesson is to review the solution to the homework done the previous night by the students.

Lesson Objectives: At the end of this lesson the student will be able to:

know if they worked the previous evening's homework problems using the correct logic and procedure; and

know if they obtained the correct answers to each problem assigned.

Student Prerequisite Skills: Air Pollution Training Institute Course 452 or equivalent experience, and one of the following: college level training in physical science, engineering, or mathematics.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

Workbook for Combustion Evaluation in Air Pollution Control

Chalkboard

Special Instructions:

The instructor should solicit questions from the students to determine if they understand the proper logic used in problem-solving and to answer any questions they may have about alternative solution techniques or assumptions.

The problem statements and the solutions are found at the end of the lesson plans for each problem session and in the workbook.

References:

1. *Combustion Evaluation in Air Pollution Control*

LESSON PLAN

AIR POLLUTION
TRAINING INSTITUTE

TOPIC: Combustion Systems Design

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: F. A. Iachetta
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 9

Lesson Goal: The goal of this lesson is to provide the student with a general understanding of how energy utilization, together with choice of fuel and fuel-firing equipment, influences system design.

Lesson Objectives: At the end of this lesson, the student will be able to:

describe the relationship between energy utilization, furnace heat transfer, and excess air as means of furnace temperature control;

understand the limits which may be imposed by thermodynamic laws and how these limits dictate choice of energy-recovery devices following the furnace;

calculate the energy required from fuel to meet an output energy requirement.

Student Prerequisite Skills: Course 427, Lessons 1 through 8.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 9

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 4.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 9: COMBUSTION SYSTEMS DESIGN
427-9-1	FURNACE DESIGN CONSIDERATIONS
427-9-2	SYSTEM ENERGY DISTRIBUTION
427-9-3	STEAM GENERATOR ENERGY DISTRIBUTION
427-9-4	ENERGY DISTRIBUTION

AIR POLLUTION TRAINING INSTITUTE

CONTENT OUTLINE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 427, Combustion Evaluation
Lecture Title: Combustion System Design

Page 3 *of* 3

NOTES

I. Introduction
   A. State the lesson objectives
   B. Discuss combustion systems as a means of providing energy for a wide variety of end-uses.
   C. Describe the influence which economics has in equipment choice.

II. Describe what a "design flow sheet" would include.
   A. Discuss the fact that requirements begin with energy output as established by a "load"
      1. Describe several loads such as electric power output, building heating system gas-fired dryers, etc.
   B. Describe the influence of fuel selection, including use of multifuels where availability may be factor
   C. Introduce the importance of overall efficiency in determining fuel-flow rates.
   D. Note that forced-draft fan or fans can be sized only after a total air-fuel relationship has been set.
   E. Describe the design of the induced draft fan and stack
      1. Point out that the choice of furnace pressure and emission control hardware influence the design of fan and stack

III. Discuss design methodology.
   A. Describe need to choose a fuel and furnace temperature
      1. Outline variables involved
      2. Point out relationships between heat transfer, excess air, etc.
      3. Note the trade-offs inherent in point 2 above; use example 4.1 as illustration
      4. Introduce energy balance for system
   B. Describe the energy utilization considerations which follow furnace design.
      1. Use steam boiler example 4.2, pg. 4-9 in Student Manual
      2. Point out the manner in which practical heat transfer values limit temperatures.
   C. Discuss further relationships which would enter design as emission control hardware is added
      1. Point out energy considerations which might be needed for different methods.
      2. Particularly note induced draft and temperature problems with scrubbers.

Slide 427-9-1

Refer to Student
Manual, 4.1, p.
4-4 through 4-8
Slide 427-9-2

Slide 427-9-3

Slide 427-9-4

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Problem Session II:
Combustion Systems Design

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: F. A. Iachetta
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 10

Lesson Goal: The goal of this lesson is to provide the student an instructor-guided opportunity to perform calculations important in combustion system design.

Lesson Objectives: At the end of this lesson the student will be able to:

calculate the energy required from fuel to meet an energy output;

calculate the furnace exit gas temperature for a given fuel-firing arrangement; and

calculate the furnace volume required to burn a given fuel.

Student Prerequisite Skills: Course 427, Lesson 9

Level of Instruction: Undergraduate engineering or equivalent

Support Materials and Equipment:

1. Workbook for Combustion Evaluation in Air Pollution Control, Chapter II.
2. Chalkboard.
3. Hand-held calculator or slide rule.

Special Instructions: Assign Problem II.2 for homework.

References:

1. Combustion Evaluation in Air Pollution Control, Chapters, 2, 4, and 6.

I. Purpose
  A. State the lesson objectives
  B. Note that this is an instructor-guided problem-solving session intended to give students practice with material presented in earlier lessons, particularly Lesson 9.
    1. The problem statements and computational sheet are found in Chapter II of the Workbook.
    2. The completed computational sheets for the instructor are found at the end of this lesson plan.

II. Methodology
  A. During the class period, guide the students through the logic and calculations required for the solution of Problem II.1: Calculation of Furnace Volume.
  B. Assign for homework Problem II.2: Furnace Volume Plan Review.
  C. During the class period, guide the students through the logic and calculations required for the solution of Problem II.3: Calculation of Furnace Gas Exit Temperature.
  D. Answers to Problem II.2 are to be confirmed during the Homework Review period.

CHAPTER II

COMBUSTION SYSTEM DESIGN PROBLEMS

PROBLEM II.1: Calculation of Furnace Volume

Consider the design of a pulverized coal-fired furnace which operates with an average energy release rate of 25,000 Btu/hr per cubic foot of furnace volume. The furnace produces steam with an energy output of 55×10^6 Btu/hr and a thermal efficiency of 80%.

Calculate:

1. The furnace volume for the steam generator.

Solution for Problem II.1:

1. Determine the fuel energy input required in order to realize the given energy output

$$Q_H = \frac{Q_s}{\eta} = \frac{55 \times 10^6 \text{ Btu/hr}}{0.80}$$

$$= \underline{68.75 \times 10^6} \text{ Btu/hr}$$

2. Refer to Table 9.6 in the Student Manual, p. 9-10, to obtain the average design value for the heat release rate of 25,000 Btu/hr ft^3 for pulverized coal firing.

$$\text{Furnace Volume} = \frac{Q_H}{25{,}000 \frac{\text{Btu}}{\text{hr ft}^3}} = \frac{(68.75 \times 10^6)}{25{,}000 \frac{\text{Btu}}{\text{hr ft}^3}}$$

$$= \underline{2{,}750} \text{ ft}^3$$

PROBLEM II.2: Furnace Volume Plan Review

An industrial organization proposes to build a 100,000 pounds-per-hour steam generator. The furnace is to be fired by a chain-grate stoker with continuous ash removal, similar to that shown in Attachment 9-4 of the Student Manual, p. 9-18. The furnace is 12 ft. wide (across the front), 14 ft. deep, and 28 ft. high. The volume corresponding to these dimensions includes the superheater volume, which is small enough to be neglected in the calculation. The fuel for the proposed unit is to be the high-volatile bituminous coal described in Attachment 3-11 of the Student Manual, p. 3-20. The steam generator will require 6 tons per hour of this coal to achieve its full steam capacity.

Determine:

1. If the furnace volume is adequate.

Solution for Problem II.2:

1. Calculate the furnace volume using the dimensions given:

Furnace volume = (length) x (width) x (height) - (superheater volume)

= (14) x (12) x (28) - (0.0)

= 4,704 ft^3

2. Calculate the energy release rate per cubic foot for the specified fuel and design capacity.

$$\text{Energy release rate} = \frac{(\text{coal firing rate}) \times (\text{higher heating value})}{(\text{Furnace volume})}$$

$$= \frac{(6 \times 2{,}000 \text{ lb/hr}) \times (13{,}325 \text{ Btu/lb})}{(4{,}704 \text{ ft}^3)}$$

= 34,000 Btu/hr ft^3

3. Compare the value obtained above to that given in Table 9.6 on p. 9-10 of the Student Manual.

PROBLEM II.3: Calculation of Furnace Gas Exit Temperature

A reheat steam generator design has energy utilization based on the total energy input (higher heat value) as follows:

1.	Energy absorbed in radiant boiler	49.5%
2.	Energy absorbed in convection superheater	20.8%
3.	Energy absorbed in economizer	6.6%
4.	Energy absorbed in steam reheater	8.0%
5.	Energy absorbed in air preheater	5.0%
6.	Furnace heat losses	3.0%
7.	Flue gas and other losses	7.1%
		100.0%

The unit is fired with pulverized coal, using the coal described as the "as received" coal listed in Attachment 3-12 on p. 3-21 of the Student Manual. The unit operates with 15% excess air; and the combustion air is preheated to 300°F.

Calculate:

1. The temperature of the gas leaving the furnace.

Solution for Problem II.3:

1. Determine the theoretical air required to burn the coal specified, using Equation 4.1 on p. 4.4 of the Student Manual. The coal is 75% carbon, 5% hydrogen, 2.3% sulfur, 1.5% nitrogen, 6.7% oxygen, 2.5% moisture, and 7.0% ash.

$$\text{Theoretical Air} = A_t = 11.53\,(C) + 34.34\,(H_2 - \frac{O_2}{8}) + 4.29\,(S)$$

$$= 11.53(.75) + 34.34\,(.05 - \frac{.06}{8}) + 4.29(.023)$$

$$= \underline{\quad 10.18 \quad}\ \text{lbs per lb of coal}$$

2. Calculate total air.

$$\text{Total Air} = A_a = (1.0 + \frac{\%\ EA}{100})\ A_t$$

$$(1.0 + \frac{15}{100}) \times (10.18)$$

$\underline{\quad 11.71 \quad}$ lbs per lb of coal.

3. Estimate the amount of flue gas produced using Equation 4.2 on p. 4-5 of the Student Manual:

Theoretical flue gas = G

$$= (m_f - \text{noncombustibles}) + m_f\ A_t$$

Choose a basis of one pound of fuel, so that $m_f = 1$:

$$G = (1.0 - \frac{\%\ Ash}{100}) + (1.0) \times A_t$$

$$= (1.0 - \frac{7}{100}) + 1.0 \times (10.18)$$

$= \underline{\quad 11.11 \quad}$ lb gas per lb of coal

$$\text{Actual flue gas} = G_f = (G + A_E) = G + \frac{\%\ EA}{100} \times A_t$$

$$= (11.11) + (\frac{15}{100}) \times (10.18)$$

$= \underline{\quad 12.64 \quad}$ lbs gas per lb of coal

4. Calculate the useful energy, Q_u, absorbed in the furnace region (radiant boiler in this case).

$$Q_u = (\text{fraction of energy absorbed in radiant boiler}) \times (\text{HHV})$$

$$= 0.495 \times (13{,}000)$$

$= \underline{\quad 6{,}435 \quad}$ Btu/lb of coal

5. Note that Q_u is also related to the energy input as follows:

Q_u = (lower heating value) - (losses) - (energy in the gases leaving furnace)

which is given by Equation 4.8 on p. 4-7 of the Student Manual.

$$Q_u = H - Q_L - G_f C_p (t_f - t_a)$$

a. The energy, H, is obtained from

H = HHV - energy of the water in flue gas

= HHV - Q_v,

where:

water in flue gas = 9.0 x (H_2 in fuel) + (as-fired moisture)

= 9.0 x (.05) + (.025)

= 0.475 lbs H_2O/lb coal

and the energy in this water is

Q_v = (lbs of water per lb fuel) x (latent heat of vaporization)

$$= (0.475)\ \frac{\text{lbs } H_2O}{\text{lbs fuel}} \times (1{,}000\ \frac{\text{Btu}}{\text{lb}})$$

= 475 Btu per lb coal

now

H = HHV - Q_v

= (13,000) - (475)

= 12,525 Btu per lb of coal

b. The losses, Q_L, are:

Q_L = fraction of energy lost from furnace x (HHV)

= (.03) x (13,000)

= 390 Btu per lb of coal

c. The furnace gas temperature is calculated by substituting values obtained from Q_u, H, Q_L, G_f together with a value for $C_p = 0.26$ Btu/lb °F and $t_a = 300°F$:

$$Q_u = H - Q_L - G_f C_p (t_f - t_a)$$

$$(6{,}435) = (12{,}525) - (390) - (12.64)\left(0.26 \frac{\text{Btu}}{\text{lb °F}}\right)(t_f - 300)$$

therefore:

t_f = 2,034 °F

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Pollution Emissions Calculations I

COURSE: 427, Combustion Evaluation
LESSON TIME: 45 min.
PREPARED BY: F. A. Iachetta
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 11

Lesson Goal: The goal of this lesson is to provide the student with basic definitions relating to emission standards and to provide them with an ability to make emission calculations employing emission factors.

Lesson Objectives: At the end of this lesson the student will be able to:

describe the nature and origin of most of the published emission factors and state what is necessary for more precise estimates of emissions from a specific installation with specified design features;

apply the proper method for using emission factors to determine estimates of emissions from typical combustion sources;

define and distinguish between concentration standards (C_{vs} and C_{ms}), pollutant mass rate standards (PMR_s), and process emission standards (E_s).

Student Prerequisite Skills: First-level college chemistry, algebra, physics (heat), and Course 427, Lessons 2 and 3.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 11

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 5.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 11: POLLUTION EMISSIONS - CALCULATIONS I
427-11-1	NOMENCLATURE OF STANDARDS
427-11-2	C_{ms}, MASS STANDARD
427-11-3	POLLUTANT MASS RATE STANDARD
427-11-4	PROCESS STANDARD
427-11-5	EMISSION FACTORS FOR FUEL OIL COMBUSTION
427-11-6	EMISSION FACTORS FOR NATURAL GAS COMBUSTION
427-11-7	SO_2 EMISSION ESTIMATE, GIVEN:
427-11-8	EMISSION ESTIMATE FROM BASIC CHEMISTRY
427-11-9	EMISSION CALCULATION
427-11-10	RECOMPUTATION WITH EMISSION FACTOR
427-11-11	PROCESS EMISSION
427-11-12	UNCONTROLLED PARTICULATE EMISSION ESTIMATE
427-11-13	FRACTIONAL COLLECTIONAL EFFICIENCIES OF PARTICULATE CONTROL EQUIPMENT

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Pollution Emission Calculations I

Page 3 *of* 4

NOTES

I. Introduction
  A. State the lesson objective
II. Definition of various standards
  A. Discuss the concentration standards
    1. Volume standards
      a. The symbol used is C_{vs}
      b. Quantity of pollutant per volume quantity at a specified temperature and pressure
      c. Examples to present: 80 μg/m^3 for ambient SO_2; 75 μg/m^3 for suspended particulate
      d. Other volume standard units can be grains/scf; lb/scf
    2. Mass standards
      a. The symbol used is C_{ms}
      b. Quantity of pollutant per mass quantity of carrier gas
      c. Units could be lbs/1,000 lbs. gas, g/kg gas, etc.
  B. Define the pollutant mass rate standards
    1. The symbol used is PMR_s
    2. Standards which fix the time rate of emission
    3. Units could be lb/hr, kg/hr, etc.
  C. Describe process emission standards
    1. The symbol used is E
    2. Standards which fix the maximum emission permitted for various kinds of processes
    3. Such standards can be based on either input energy or input raw material to a process
    4. Examples to present:
      a. Combustion source standards with allowable mass of emission per energy input (expressed in millions of Btu/hr or million of kJ/hr)
      b. New source performance standards for a power plant
III. Emission Factors — Stationary Combustion Sources
  A. Define the emission factor with particular attention to the need for careful qualification
    1. Tabulated information appears in AP-42
    2. These factors are for systems without pollution controls
    3. The meaning of the ratings A, B, C, etc., as set forth in AP-42 need careful explanation
    4. SO_x is essentially fixed by fuel sulfur content, while other emissions can be influenced by the design or operation of a system
  B. Outline methods used to estimate uncontrolled emissions
    1. Basic chemistry indicates that 40 S is the maximum SO_2 which can be expected from a given fuel such as bituminous coal
    2. The SO_2 emission factor is 38 S
      a. This is a lower value because of: sulfur in bottom ash and SO_3 produced
    3. Coal ash percentage can be used to calculate an uncontrolled particulate emission for a spreader stoker

Slide 427-11-1
Slide 427-11-2
Slide 427-11-3
Slide 427-11-4

Standard P_s, T_s
29.92 in Hg, 60°F
or 760 mmHg, 25°C

Refer to Student Manual, Attachment 5-1, pp.5-20

Refer to Student Manual, p. 5-30
Slide 427-11-5
Slide 427-11-6

Slide 427-11-7
Slide 427-11-8
Slide 427-11-9
Slide 427-11-10

Refer to Student Manual, p. 5-30
Slide 427-11-11
Slide 427-11-12

a. Describe the influence of ash reinjection

C. Carefully point out the influence of particulate size distribution on collection efficiency

1. Size distribution of an input solid fuel has a direct influence on particulate size distribution in the stack gas
2. Particulate collection devices have different efficiencies for different density. Emphasize that collection efficiency varies with density
3. Particle size vs collection efficiency

Slide 427-11-13
Data based on
ρ_p = 2.7 g/cm^3

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Pollution Emission Calculations I

Page 4 of 4

NOTES

   a. Describe the influence of ash reinjection

C. Carefully point out the influence of particulate size distribution on collection efficiency
   1. Size distribution of an input solid fuel has a direct influence on particulate size distribution in the stack gas
   2. Particulate collection devices have different efficiencies for different density. Emphasize that collection efficiency varies with density
   3. Particle size vs collection efficiency

Slide 427-11-13
Data based on
$\rho_p = 2.7\ g/cm^3$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Problem Session III:
Emission Calculations I

COURSE: 427, Combustion Evaluation
LESSON TIME: 45 min.
PREPARED BY: F. A. Iachetta
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 12

Lesson Goal: The goal of this lesson is to provide the computational methodology used in estimating the amount of air pollutants and the degree of control required.

Lesson Objectives: At the end of this lesson the student will be able to:

use average emission factors to estimate the emissions from typical combustion installations;

calculate the degree of control required for a given source to be brought into compliance with a given emission standard; and

perform calculations using the relationships between anticipated SO_2 emissions and the sulfur content of liquid and solid fuels.

Student Prerequisite Skills: College albegra; Course 427, Lesson 11

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Workbook for Combustion Evaluation in Air Pollution Control, Chapter III.

Special Instructions: This is an instructor-guided problem session.

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 5.

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Problem Session III

NOTES

I. Purpose
   A. State the lesson objectives.
   B. Note that this session serves as an instructor-guided work session, which provides the student an opportunity to apply definitions set forth in Lesson 11.
      1. The problem statements and computational sheets are found in Chapter III of the Workbook.
      2. The computational sheets with correct answers for the instructor are found at the end of this lesson plan.

II. Methodology
   A. During the class period, guide the students through the logic and calculations required for the solution to each part of Problem III.1: Pollutant Emissions from Coal-Fired Power Plant.
   B. During the class period, guide the students through the logic and calculations required for the solution to Problem III.2: Fuel Sulfur Limit Calculation.
      1. Discuss the assumptions which were made and how actual variations from these assumptions would influence the conclusions.

CHAPTER III

EMISSION CALCULATIONS I

PROBLEM III.1: Pollutant Emissions from Coal-Fired Power Plant

Plans call for a 500 MW_e power plant to have a dry-bottom design and to burn pulverized coal. The overall thermal efficiency is designed to be 34%. The coal specified in the plans contains 1.3% sulfur, 22% ash, and has a 12,500 Btu/lb HHV.

Compute:

1. The input energy required when the unit is operated at the rated capacity.
2. The coal firing rate at the rated capacity.
3. The pollutant mass rate for emissions of:
    a. SO_2
    b. Particulates
    c. NO_x
    d. HC
    e. CO
4. The process emissions per million Btu of energy input for
    a. SO_2
    b. Particulates
5. The degree of control required to meet a 1.2 lb $SO_2/10^6$ Btu performance standard for SO_2.
6. The degree of control required to meet a 0.1 lb particulate/10^6 Btu performance standard for particulates.

Solution to Problem III.1:

1. Plant electric output rating and thermal efficiency can be used to find energy input from Equation 4.9, on p. 4-8 of the Student Manual.

$$Q_H = \text{energy in} = \frac{\text{energy out}}{\text{thermal eff}} = \frac{Q_s}{\eta}$$

$$= \frac{(\ 500\ )\ MW_e}{(\ .34\ )} \times 3413 \times 10^3\ \frac{Btu}{MW_e\ hr}$$

$$= \underline{\ 5{,}019 \times 10^6\ }\ \frac{Btu}{hr}$$

2. With the value of Q_H and the coal HHV, the coal-firing rate is given by:

$$m_f = \text{coal fired, } \frac{Ton}{hr} = \frac{Q_H}{\text{HHV per ton}} = \frac{(5{,}019 \times 10^6\ )\ \frac{Btu}{hr}}{(\ 12{,}500\ )\ \frac{Btu}{lb} \times 2{,}000\ \frac{lb}{ton}}$$

$$= \underline{\ 201\ }\ \frac{Ton}{hr}$$

3a. The pollutant mass rate for SO_2 can be obtained using the coal-firing rate and the emission factor for SO_2 (refer to Student Manual, p. 5-30 for emission factors)

$$(PMR)_{SO_2} = 38 \times S\ \frac{lb\ SO_2}{ton\ coal} \times m_f\ \frac{ton\ coal}{hr}$$

$$= 38 \times (\ 1.3\ )\ \frac{lb\ SO_2}{ton\ coal} \times (\ 201\ )\ \frac{ton\ coal}{hr}$$

$$= \underline{\ 9{,}929\ }\ lb\ SO_2/hr$$

b. $(\text{PMR})_{\text{part.}} = 17 \times A \frac{\text{lb part.}}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= 17 \times (\; 22 \;) \frac{\text{lb part.}}{\text{ton coal}} \times (\; 201 \;) \frac{\text{ton coal}}{\text{hr}}$

$= \underline{\; 75{,}174 \;}$ lb part./hr

c. Similarly, the PMR for NO_x would be

$(\text{PMR})_{NO_x} = 18 \frac{\text{lb } NO_x}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= 18 \frac{\text{lb } NO_x}{\text{ton coal}} \times (\; 201 \;) \frac{\text{ton coal}}{\text{hr}}$

$= \underline{\; 3{,}618 \;}$ lb NO_x/hr

Similarly the PMR's for CO and HC are:

d. $(\text{PMR})_{HC} = (\; 0.3 \;) \frac{\text{lb HC}}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= (\; 0.3 \;) \times (\; 201 \;)$ lb HC/hr

$= \underline{\; 60.3 \;}$ lb HC/hr

e. $(\text{PMR})_{CO} = (\; 1.0 \;) \frac{\text{lb CO}}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= (\; 1.0 \;) \times (\; 201 \;)$ lb CO/hr

$= \underline{\; 201 \;}$ lb CO/hr

4a. The SO_2 process emissions per million Btu energy input will be computed from the SO_2 pollutant mass rate and the input energy rate:

$$E_{SO_2} = \frac{(PMR)_{SO_2}}{Q_H}$$

$$= \frac{(9{,}929\ )\ \frac{\text{lb } SO_2}{\text{hr}}}{(5{,}019 \times 10^6)\ \frac{\text{Btu}}{\text{hr}}}$$

$$= \underline{\quad 1.98 \quad}\ \frac{\text{lb } SO_2}{10^6 \text{ Btu}}$$

b. The particulate emissions per million Btu energy input will be computed similarly:

$$E_{part} = \frac{(PMR)_{part}}{Q_H}$$

$$= \frac{(75{,}174)\ \text{lb particulates/hr}}{(5{,}019 \times 10^6)\ \text{Btu/hr}}$$

$$= \underline{\quad 14.98 \quad}\ \frac{\text{lbs}_{part}}{10^6 \text{ Btu}}$$

5. The computations presented above can be used to compute the degree of control required to meet a given emission standard. For this problem the performance standards are listed on p. 5-20 in the Student Manual. For a solid-fuel-fired power plant which is 250 x 10^6 Btu/hr or larger, the SO_2 standard is 1.2 lb $SO_2/10^6$ Btu.

From above the calculated E_{SO_2} = ___1.98___ lb $SO_2/10^6$ Btu

Therefore,

Degree of control needed $= \dfrac{E_{SO_2} - \text{Standard}}{E_{SO_2}} \times 100\%$

$= \dfrac{(\ 1.98\ ) - 1.2}{(\ 1.98\ )} \times 100\%$

$=$ __39.4__ % reduction of the uncontrolled value

6. Similarly the particulates standard is 0.1 lb/10^6 Btu and the estimated uncontrolled particulates was

$E_{part} = (\ 14.98\ )\ \dfrac{\text{lb particulates}}{10^6\ \text{Btu}}$

Degree of control needed $= \dfrac{E_{part} - \text{Standard}}{E_{part}} \times 100\%$

$= \dfrac{(\ 14.98\ ) - .1}{(\ 14.98\ )} \times 100\%$

$=$ __99.3__ % reduction of the uncontrolled value

PROBLEM III.2: Fuel Sulfur Limit Calculation

A 22-degree API fuel oil is to be burned subject to a maximum SO_2 emission standard of 0.8 lb $SO_2/10^6$ Btu input.

Determine:

1. The maximum sulfur composition of the 22-dgree API fuel oil which meets the standard without flue gas desulfurization.

Solution to Problem III.2:

From Student Manual, Attachment 3-5, p. 3-15, find:

total heat of combustion at constant volume = 19,110 Btu/lb_m

One should note that SO_2 is 1/2 oxygen and 1/2 sulfur by weight.

Therefore,

$$\text{Max S} = \frac{.5 \text{ lb S}}{\text{lb } SO_2} \times \frac{(0.8 \text{ lb}_m\ SO_2)}{10^6 \text{ Btu}} \times \frac{(\ 19{,}110\ ) \text{ Btu}}{\text{lb}_m \text{ oil}}$$

$$= \underline{\quad 0.0076 \quad} \frac{\text{lb}_m \text{ S}}{\text{lb}_m \text{ oil}}$$

$$= \underline{\quad 0.76 \quad} \% \text{ S in the oil}$$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Pollution Emission Calculations II

COURSE: 427, Combustion Evaluation
LESSON TIME: 90 min.
PREPARED BY: F. A. Iachetta
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number 13

Lesson Goal: The goal of this lesson is to provide the student with the computational methods typically used in determining excess air and in correcting measured concentrations to a standard basis.

Lesson Objectives: At the end of this lesson the student will be able to:

identify the proper equation for computing excess air from an Orsat analysis of the flue gas of a combustion installation;

state the reasons for expressing concentrations at standard conditions of temperature pressure, moisture content and excess air;

identify and use the proper factors for correcting field measurements to a standard basis, such as 50% excess air, 12% CO_2, and 6% O_2;

use F-factors to estimate emissions from a combustion source.

Student Prerequisite Skills: Course 427, Lessons 11 and 12.

Level of instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 13.

Special Instructions: None.

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 5.

2. "Requirements for Submittal of Implementation Plans and Standards for New Stationary Sources," Federal Register 40:194, Part V (October 6, 1975).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 13: POLLUTION EMISSION CALCULATIONS II
427-13-1	GAS VOLUME CORRECTIONS
427-13-2	GAS CORRECTIONS FOR CONCENTRATION
427-13-3	GAS CORRECTIONS FOR DENSITY
427-13-4	EXCESS AIR CORRECTIONS
427-13-5	CORRECTIONS TO 50% EXCESS AIR
427-13-6	CORRECTIONS TO 12% CO_2
427-13-7	CORRECTIONS TO 6% O_2
427-13-8	EXCESS AIR PERCENT
427-13-9	EXAMPLE WITHOUT EXCESS AIR
427-13-10	EXAMPLE WITH EXCESS AIR
427-13-11	EXCESS AIR FROM ORSAT ANALYSIS
427-13-12	SAMPLE OF ORSAT DATA APPLICATION
427-13-13	CALCULATE % EXCESS AIR
427-13-14	EXAMPLE PROCESS EMISSION STANDARD
427-13-15	DEFINITION OF AN "E" STANDARD PROBLEM
427-13-16	SOLUTION OF SAMPLE "E" PROBLEM
427-13-17	ALLOWABLE EMISSION
427-13-18	ACTUAL PARTICULATE RATE
427-13-19	F-FACTOR CONCEPT
427-13-20	EMISSION IN TERMS OF F-FACTOR
427-13-21	EQUATIONS FOR F_c FACTOR
427-13-22	EQUATION FOR F_o FACTOR
427-13-23	TABLE OF F-FACTORS

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Pollution Emission Calculations II

	NOTES
I. Introduction	
A. State the lesson objectives	
B. Outline the method for correcting volume field measurements (at actual temperature and pressure) to standard pressure temperature.	
1. Concentration standards are based on pressure and temperature standards.	Refer to Student Manual, Chap. 5
2. The equation for correction of volume (measured at field pressure P_o and temperature T_o) to equivalent volume at P_s, T_s.	Slide 427-13-1 Equation 1
3. Necessary nomenclature and equations for corrections of concentration, C_v, and of density, ρ.	Slides 427-13-2,3 Equations 2 & 3
C. Discuss the basis for corrections of concentration which are developed in terms of 50% excess air, 12% CO, 6% O_2, etc.	Slide 427-13-2 Equations 4, 5, 6, 7, & 8 Slides 427-13-4,5, 6, & 7 Equations 11, 12, 13, & 14
1. Parameter selection was originally based on a "reasonable" value for a wide variety of combustion equipment	
2. Effective standards eliminate dilution as a solution to pollution	
II. The Chemistry of Excess Air	Slide 427-13-8
A. Elaborate on the basic chemistry of combustion with excess air	
1. Basic stoichiometric relationship for the combustion of carbon	Slide 427-13-9
a. Air is assumed to be 20.9 O_2 and 70.1% N_2.	
b. The above noted volume proportion is simply another way of stating that O_2 is 0.264 times N_2. Use information on Slide 427-13-4 to illustrate equivalence concept.	
2. Introduction of excess air into the combustion process.	
a. Excess air simply passes through the process and re-appears in stack gas. Note that CO_2 and N_2 in the theoretical case do not change with excess air added	
b. The effect of nitrogen in the fuel influence on the stack gas nitrogen	
B. Discuss the Orsat analysis	
1. The chemical equation should be recast to include a term for the oxygen and the nitrogen in excess air.	Slide 427-13-10
2. The effect of CO means increased O_2 and reduced CO_2 for a given fuel. Show that excess air is based on complete combustion; i.e., all carbon oxidized to CO_2 and all hydrogen to water.	Slide 427-13-11
3. The use of Orsat analysis to compute excess air should be illustrated.	Slide 427-13-12 Slide 427-13-13
a. SO_2 must be measured separately and deducted from observed CO_2 measurement. CO_2 reagent also absorbs SO_2.	
b. The degree of resolution for an Orsat analysis is ±0.1%.	

III. Discussion of Computations
  A. Process rate standards
    1. Introduce a particulate emission standard based on the energy input to a combustion system as one example of a process rate standard

Slide 427-13-14

      a. Data is needed to define a situation where the standard presented would be applied.

Slide 427-13-15

      b. Computations should be outlined

Slide 427-13-16, 17, & 18

  B. Corrections for excess air, CO_2, and O_2
    1. Present and discuss typical data for a boiler plant stack effluent.

Refer to Student Manual, p. 5-9

      a. Field measurement would be made at an actual temperature and pressure.
      b. Apparent molecular weight of stack gas can be determined from flue gas analysis.
      c. Mass rate of pollutant flow would be found from an appropriate measurement and would be field data.
    2. Illustrate calculations required to correct concentration based on field measurement to equivalent values.
      a. Corrections are made to a standard temperature, pressure, and dry gas basis
      b. Use of an excess air correction factor is needed for 50% excess air.
      c. Computations of correction to 12% CO_2 and 6% O_2.

Refer to Student Manual, p. 5-10, 5-11

  C. Use of F-Factors
    1. Discuss the nature of the F-factor in comparison with previously developed excess air corrections:

Slide 427-13-19

      a.

$$E = \frac{C_{vs}\,Q_s}{Q_H}$$

where C_{vs} is the concentration, Q_s is the stack gas volume flow rate, and Q_H is the heat input rate.

      b. Show that

$$\frac{C_{vs}\,Q_s}{Q_H} = C_{vs}\,F\,\left(\frac{20.9}{20.9 - \%O_{2p}}\right),$$

Slide 427-13-20

where F is simply Q_s/Q_H and the bracketed term is an excess air correction.

      c. F-factor method is directed to calculation of particulate emission levels from new sources and requires only O_2 or CO_2 content of stack be monitored in addition to pollutant concentration (1).
    2. Introduce table of F-factors and summary of equations for F_d, F_c.

Slides 427-13-21
427-13-22
427-13-23

    3. Describe errors which can result from use of F-factors:
      a. Variation of F-factor due to variations of fuel ultimate analysis

b. Effect of incomplete combustion
c. Erroneous O_{2p} and CO_{2p} values from Orsat analysis, an error also inherent in earlier methods
d. Reduction of CO_2 content of stack gas when wet scrubbers are used.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Problem Session IV : Emission Calculations II

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: F. A. Iachetta **DATE:** Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 14

Lesson Goal: The goal of this lesson is to provide the computational methodology required to reduce field-measured data to a basis that permits comparative evaluation with standards.

Lesson Objectives: At the end of this lesson, the student will be able to:

calculate excess air, given Orsat analysis data;

calculate corrected emissions based on standards specifying 50% excess air, 12% CO_2, and 6% O_2; and

employ F-factor to estimate emissions from a combustion source.

Student Prerequisite Skills: Course 427, Lessons 11, 12, 13

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Workbook for Combustion Evaluation in Air Pollution Control, Chapter IV.
2. Chalkboard.
3. Hand-held calculator or slide rule.

Special Instructions: Assign Problems VI.3 and VI.5 for homework.

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 5.

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Problem Session IV

NOTES

I. Purpose
   A. State the lesson objective
   B. Note that this is an instructor-guided problem-solving session, intended to give students practice with the material presented in Lesson 13.
      1. The problem statements and computational sheets are found in Chapter IV of the Workbook.
      2. The computational sheets with correct answers for the instructor are found at the end of this lesson plan.

II. Methodology
   A. During the class period, guide the students through the logic and calculations required for solution to Problem IV.1: Excess Air Calculations Based on Orsat Analysis.
   B. During the class period, guide the students through the logic and calculations required for the solution of Problem IV.2: Use of F-Factors to Compute Emission Concentrations.
   C. Assign as homework Problem IV.3: Calculation of F-Factor
   D. Assign Problem IV.4 to be done by the students during the class period.
   E. Assign as homework Problem IV.5: Correction of NO_X Emissions Concentration to 3% O_2.
   F. Answers to Problems IV.3 and IV.5 are to be confirmed in the Homework Review period.

CHAPTER IV

EMISSION CALCULATIONS II

PROBLEM IV.1: Excess Air Calculation Based on Orsat Analysis

The effluent of a combustion unit is characterized by:

Orsat Analysis:	11% CO_2, 9% O_2, 2% CO
SO_2:	120 ppm
Gas Flow:	200,000 acfm @ 27.5 in.Hg pressure, 340°F temperature, 8% moisture by volume
Particulates:	400 grain per acfm

Calculate:

1. The percentage of excess air in the flue gas using Equation 1 from Attachment 5-4, p. 5-23 of the student manual.
2. The SO_2 emissions in micrograms per cubic meter ($\mu g/m^3$).
3. The volume of the dry flue gas at the observed conditions.
4. The volume of the dry flue gas at standard conditions which are a pressure of 30.00 inches of mercury and a temperature of 60°F.
5. The particulate concentration based on standard pressure and temperature.
6. The particulate emission concentrations corrected for
   a. 50% excess air
   b. 12% CO_2
   c. 6% O_2

Solution for Problem IV.1:

1. Refer to Student Manual, p. 5-23, to obtain the equation for computing the excess air from an Orsat analysis.

$$EA = \frac{(O_{2p} - 0.5\ CO_p)}{0.264\ N_{2p} - (O_{2p} - 0.5\ CO_p)} \times 100\%$$

The nitrogen in the product gas, N_{2p}, may be calculated as follows:

$$N_{2p} = 100 - \%CO_2 - \%O_2 - \%CO$$

$$= 100 - (\ 11\ ) - (\ 9\ ) - (\ 2\ )$$

$$= \underline{\quad 78 \quad}\ \%\ N_2$$

Substitute the above value into equation for EA:

$$EA = \frac{(\ 9\ ) - 0.5\ (\ 2\ )}{0.264\ (\ 78\ ) - (\ 9\ - 0.5\ (\ 2\ ))}$$

$$= \underline{\quad 63.5 \quad}\ \%\ \text{excess air}$$

2. Convert 120 SO_2 ppm to $\mu g/m^3$ using Equation 5.8 on p. 5-5 of the Student Manual:

$$1\ \text{ppm} = 40.8 \times (MW) \frac{\mu g}{m^3}$$

$$1\ \text{ppm}\ SO_2 = 40.8 \times (\ 64\ ) \frac{\mu g}{m^3} = \underline{\quad 2,611 \quad} \frac{\mu g}{m^3}$$

$$120\ \text{ppm}\ SO_2 = 120 \times (\ 2,611\ ) \frac{\mu g}{m^3} = \underline{\quad 313,344 \quad} \frac{\mu g}{m^3}$$

Reduce the $\frac{\mu g}{m^3}$ units to $\frac{mg}{m^3}$, by noting that

$$1{,}000 \times \frac{\mu g}{m^3} = 1 \frac{mg}{m^3}$$

Therefore

$$120 \text{ ppm } SO_2 = (313{,}344) \frac{\mu g}{m^3} \times 10^{-3} \frac{mg}{\mu g}$$

$$= \underline{\quad 313 \quad} \frac{mg}{m^3}$$

3. Calculate the volume of the gas as follows:

$$V_{o\ dry} = V_{o\ wet} \ (1.0 - \text{moisture})$$

$$= (200{,}000)\ (1.0 - 0.08)$$

$$= \underline{\quad 184{,}000 \quad} \text{ cfm}$$

4. Refer to the Student Manual, Equation (1) on p. 5-22 and reduce $V_{o\ dry}$ to $V_{s\ dry}$, using P_s = 30.00 Hg and Ts = 520 R

$$V_s = V_o \left[\frac{P_o}{P_s}\right] \left[\frac{T_s}{T_o}\right]$$

$$= (184{,}000) \times \frac{(27.5)}{(30.0)} \times \frac{(520)}{(800)}$$

$$= \underline{\quad 109{,}633 \quad} \text{ scfm}$$

5. Likewise reduce the particulate loading concentration to that at the standard conditions

$$C_{vs} = C_{vo} \left[\frac{P_s}{P_o}\right] \left[\frac{T_o}{T_s}\right]$$

$$= (\ 400\ ) \times \frac{(\ 30.0\ )}{(\ 27.5\ )} \times \frac{(\ 800\ )}{(\ 520\ )}$$

$$= \underline{\quad 671 \quad} \text{ grain/scfm}$$

6a. Refer to the Student Manual, p. 5-23 and use Equations (2) and (3) to calculate the particulate concentrations on a 50% excess-air basis

$$F_{50V} = 1 - \left[\frac{1.50\ O_{2p} - 0.133\ N_{2p} - 0.75\ CO_p}{0.21} \right]$$

$$= 1 - \left[\frac{1.50\ (\ 0.09\ ) - 0.133\ (\ 0.78\ ) - 0.75\ (0.02\ )}{0.21} \right]$$

$$= \underline{\quad 0.923 \quad}$$

$$C_{50V} = \frac{C_{vs}}{F_{50V}} = \frac{(\ 671\ )}{(0.923\ )} = \underline{\quad 727 \quad} \text{ grain/scfm}$$

b. Correct to 12% CO_2, using Equations (6) and (7) on p. 5-23 of the Student Manual

$$F_{12V} = \frac{CO_{2p}}{0.12} = \frac{(\ 0.11\ )}{(\ 0.12\ )} = \underline{\quad 0.917 \quad}$$

$$C_{12V} = \frac{C_{vs}}{F_{12V}} = \frac{(\ 671\ )}{(0.917\ )} = \underline{\quad 732 \quad} \text{ grain/scfm}$$

c. Correct to 6% O_3 using Equations (10) and (11); however, note that Equation (10) should be modified for the net O_2 (after the CO is oxidized):

$$F_{6V} = \frac{0.21 - (O_{2p} - 0.5\ (CO_p))}{0.15}$$

$$= \frac{0.21 - (\ 0.09 \quad - 0.5\ (\ 0.02\ ))}{0.15}$$

$$= \underline{\quad 0.867 \quad}$$

$$C_{6V} = \frac{C_{vs}}{F_{6V}} = \frac{(\ 671\ )}{(\ 0.867\ )} = \underline{\quad 774 \quad} \text{ grain/scfm}$$

(IV-5)

PROBLEM IV.2: Use of F-factors to Compute Emission Concentrations

The effluent from a bituminous coal-fired source is found to have a particulate concentration, C_{vs}, equal to 671 grains/scfm (dry basis). The flue gas oxygen is 9% and the carbon monoxide is 2%, as measured on a dry basis.

Calculate:

1. The particulate emissions in the units of (grains/million Btu) using the F-factor technique

Solution to Problem IV.2:

From Attachment 5-4, p. 5-25, of the Student Manual, find:

$$F_d = \underline{9,820} \frac{\text{dscf}}{10^6 \text{ Btu}}$$

with the given C_{vs} value and the computed F_d, use Equation (5.32), p. 5-16, to calculate E, the particulate emissions, grains/10^6 Btu

$$E = C_{vs} \; F_d \left[\frac{20.9}{20.9 - (O_{2p} - 0.5 \; CO_p)} \right]$$

$$= (\; 671 \;) \times (9,820 \times 10^{-6}) \left[\frac{20.9}{20.9 - (\; 0.09 - 0.5 \; (\; 0.02))} \right]$$

$$= \underline{\; 10.67 \;} \text{ grains}/10^6 \text{ Btu}$$

PROBLEM IV.3: Calculation of F-factor

F-factors are useful in the calculation of emissions from combustion sources. Consider a bituminous coal having the "as-fired" ultimate analysis of 75% carbon, 5% hydrogen, 6.7% oxygen, 1.5% nitrogen, 2.3% sulfur, 7.0% ash, and 2.5% free moisture. The heating value of this coal is 13,000 Btu/lb.

Calculate:

1. The F-factor, F_d, using the Equation 5.28 on p. 5-15 of the Student Manual and compare this value with that given in Attachment 5-5, p. 5-25, of the Student Manual.

Solution to Problem IV.3:

The equation for the F-factor, F_d, is

$$F_d = \frac{(3.64\ H_2 + 1.53\ C + 0.57\ S + 0.14\ N - 0.46\ O_2)}{HHV} 10^6 \quad \frac{dscf}{10^6\ Btu}$$

$$= \frac{[3.64\ (5) + 1.53\ (75) + 0.57\ (2.3) + 0.14\ (1.5) - 0.46\ (6.7)]}{(13{,}000)}$$

$$= \frac{10{,}581}{} \quad \frac{dscf}{10^6\ Btu}$$

(IV-7)

PROBLEM IV.4: Calculation of Pollutant Concentration

Bituminous coal is burned completely at a rate of 5 ton/hr with excess air. An evaluation of the effluent yields the following data:

Orsat Analysis:	CO_2	9.1%
	O_2	10.6%
	CO	0.0%
Volume Flow:	26,000 scfm	
Pollutant Mass Rate:	130,000 grains/min.	

Compute:

1. The particulate concentration corrected to 50% excess air.
2. The particulate concentration corrected to 12% CO_2.
3. The particulate concentration corrected to 6% O_2.

Solution to Problem IV.4:

1. Find the particulate concentration, C_{vs}, using the flow and the pollutant mass rate from Equation 5.21, p. 5-14 of the Student Manual:

$$C_{vs} = \frac{PMR}{V_s}$$

$$= \frac{(130{,}000)\ \text{grains/min.}}{(\ 26{,}000)\ \ \text{scfm}}$$

$$= \underline{\quad 5 \quad}\ \text{grains/scf}$$

Correct the concentration to 50% excess air using Equations (2) and (3) on p. 5-23 of the Student Manual

$$F_{50v} = 1 - \left[\frac{1.5\ O_{2p} - 0.133\ N_{2p} - 0.75\ CO_p}{0.21}\right]$$

$$= 1 - \left[\frac{1.5\ (0.106) - 0.133\ (0.803) - 0.75\ (\ 0.0\ \ )}{0.21}\right]$$

$= 1 - (0.249)$

$= \underline{\quad 0.751 \quad}$

$$C_{50v} = \frac{C_{vs}}{F_{50_{vs}}} = \frac{(5)}{(0.751)}$$

$= \underline{\quad 6.65 \quad}$ grains/scf at 50% EA

2. Correct the concentration to 12% CO_2 using Equations (6) and (7) on p. 5-23 of the Student Manual

$$F_{12v} = \frac{CO_{2p}}{0.12} = \frac{(.091)}{.12}$$

$= \underline{\quad 0.758 \quad}$

$$C_{12v} = \frac{C_{vs}}{F_{12}} = \frac{(5)}{(0.758)}$$

$= \underline{\quad 6.59 \quad}$ grains/scf at 12% CO_2

3. Correct the concentration to 6% O_2 using Equations (10) and (11) on p. 5-24 of the Student Manual

$$F_{6v} = \frac{0.21 - O_{2p}}{0.15} = \frac{0.21 - (0.106)}{0.15}$$

$= \underline{\quad 0.693 \quad}$

$$C_{6v} = \frac{C_{vs}}{F_{6v}} = \frac{(5)}{(0.693)}$$

$= \underline{\quad 7.21 \quad}$ grains/scf at 6% O_2

PROBLEM IV.5: Correction of NO_X Emission Concentration to 3% O_2

Limiting the excess air during combustion is an important technique for controlling the NO_X emissions. In order to provide a more meaningful basis for comparison, the resulting emissions will be corrected to a standard basis of 3% O_2 (or 3% excess O_2). Consider the NO_X emissions of 200 and 300 ppm from an oil-fired power plant under the stack gas conditions A and B, respectively (which have different conditions of excess air).

Condition	Dry Volume Basis			
	CO_2, %	O_2, %	N_2, %	NO_X, ppm
A	13.3	2.2	84.5	200
B	9.7	7.3	83.0	300

Determine:

1. The excess air corresponding to conditions A and B.
2. The correction factor to be used in correcting NO_X emissions from their actual condition to the basis of 3% O_2.
3. The corresponding values of NO_X at the standard basis of 3% oxygen.

Solution to Problem IV.5:

1. Find the excess air for conditions A and B using Equation (1) on p. 5-23 of the Student Manual.

$$\%EA = \left[\frac{O_{2p} - 0.5\ CO_p}{0.264\ N_2 - (O_{2p} - 0.5\ CO_p)}\right] \times 100\%$$

For condition A:

$$\%EA = \left[\frac{(\ .022\ ) - 0.5\ (0.0\ )}{0.264\ (.845\ ) - (.022 - 0.5\ (\ 0.0\ ))}\right] \times 100\%$$

$= \underline{\quad 10.9\% \quad}$ for condition A.

(IV-10)

For condition B:

$$\%EA = \left[\frac{(\ .073\ ) - 0.5\ (0.0\ )}{0.264\ (\ .83) - (.073 - 0.5\ (\ 0.0))}\right] \times 100\%$$

= 50.0 for condition B.

2. The volume correction factor for flue gas O_2 is derived from

$$F_{O_2v} = \frac{0.21 - O_{2p}}{0.21 - O_{2\ std}}$$

$$F_{3v} = \frac{0.21 - O_{2p}}{0.21 - 0.03}$$

$$= \frac{0.21 - O_{2p}}{(\ .18\ )}$$

3. Use the correction factor developed above, to correct the measured NO_x emissions at conditions A and B to the 3% O_2 standard basis:

For 200 ppm NO_x at 10.9 % excess air

$$C_{3v} = \frac{C_v}{F_{3v}} = \frac{200\text{ ppm}}{\frac{.21 - (.022)}{.18}}$$

= 191 ppm corrected to 3% O_2

For 300 ppm NO_x at 50 % excess air

$$C_{3v} = \frac{C_v}{F_{3v}} = \frac{300}{\frac{.21 - (\ .073\ )}{.18}} = 394$$ ppm corrected to 3% O_2

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Introduction to Combustion Control

COURSE: 427, Combustion Evaluation
LESSON TIME: 75 min.
PREPARED BY: F. A. Iachetta
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 15

Lesson Goal: The goal of this lesson is to provide an overview of the logic for control of combustion systems and special features of control systems.

Lesson Objectives: At the end of this lesson, the student will be able to:

list the important variables (steam pressure, steam flow rate, gas temperature) which may serve as the controlled variables used to actuate fuel/air controls for combustion systems;

describe the primary purpose of a control system which is to maintain combustion efficiency and thermal states;

understand the interrelationships between varying load (energy output) requirements and both fuel/air flow and excess air;

Student Prerequisite Skills: Course 427, Lessons 2, 3, 6, and 9

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector and 16 mm sound movie projector.
2. Slide set for Lesson 15.
3. Film — "Boilers and Their Control."

Special Instructions: Show the film after the first 30 minutes of the lesson period.

References:

1. *Combustion Evaluation in Air Pollution Control*, Chapter 6.

2. *North American Combustion Handbook*, Second Edition, North American Manufacturing Company, Cleveland, Ohio (1973).

3. *Steam, Its Generation and Use*, Chapter 35, 39th Edition, Babcock and Wilcox Company, 1978.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 15: INTRODUCTION TO COMBUSTION CONTROL
427-15-1	SCHEMATIC OF STEAM-FLOW ORIFICE STATION
427-15-2	ACTUAL STEAM-FLOW ORIFICE STATION
427-15-3	STEAM-FLOW DIFFERENTIAL SENSING AND TRANSFER UNIT
427-15-4	AUTOMATIC FORCED-DRAFT FAN INLET LOUVER CONTROL
427-15-5	AUTOMATIC GAS-FLOW CONTROL VALVE
427-15-6	DIAGRAM OF A COMBUSTION CONTROL FOR A SPREADER-STOKER FIRED BOILER
427-15-7	DIAGRAM OF A COMBUSTION CONTROL FOR A GAS- AND OIL-FIRED BOILER
427-15-8	DIAGRAM OF A COMBUSTION CONTROL FOR A PULVERIZED-COAL FIRED BOILER
427-15-9	DIAGRAM OF A COMBUSTION CONTROL FOR A CYCLONE-FIRED BOILER

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Introduction to Combustion Control

Page 4 *of* 6

NOTES

I. Introduction
   A. State lesson objectives
   B. Describe primary function of combustion control
      1. System must maintain combustion efficiency while controlling emissions
      2. Control must permit maintenance of pre-determined values of temperature, pressure, etc., in systems to which energy is supplied
      3. There is a requirement to accomplish the above under all conditions

II. Specific requirements of combustion control
   A. Note that all systems must alter fuel input rate proportional to energy output while simultaneously adjusting the air/fuel ratio
   B. Describe interrelationships between fuel change and other variables:
      1. Steam pressure and/or steam flow
      2. Interactions between forced draft, induced draft, and furnace draft.
      3. The importance of fuel properties and the range of controls should be appreciated.
         a. There is an influence from high-moisture content.
   C. Discuss control logic for stoker-fired coal-burning units:
      1. The interaction between steam pressure actuated fuel feed and "steam-flow air-flow" actuated air supply
      2. Separate furnace draft control element
   D. Describe the control systems usually employed for gas- and oil-fired boilers
      1. Steam pressure is used as a prime controlled variable
      2. Cross limits are built in for regulation of air flow and fuel flow.
      3. There is a separate control leg when atomizing steam is used.
   E. Discuss pulverizer coal-burning controls
      1. The master fuel flow controller considers the total flow versus load characteristics
      2. The air-flow/fuel-flow relationship is one of parallel application.
      3. The low-select auctioneer action when air flow is low should be discussed, relative to coal flow rate.
   F. Discuss cyclone furnace combustion controls
      1. Each cyclone functions as an individual furnace
      2. The use of multi-cyclones as multiple furnaces should be described
      3. The O_2 analyzer has been specifically included to fine tune excess air

III. Film — "Boilers and Their Control"
   A. Show the film (30 minutes)
   B. Review and discuss the major points presented in the film:
      1. Two types of boilers are:

Slide 427-15-1
Slide 427-15-2, 3
Slide 427-15-4

Slide 427-15-5

Slide 427-15-6
Refer to Student Manual, p. 6-12. Attachment 6-1, for definition of control symbols
Slide 427-15-7

Slide 427-15-8

Slide 427-15-9

   a. Fire-tube boilers
   b. Water-tube boilers
2. Three primary boiler circuits are:
   a. Steam and water circuit
   b. Flue gas and air circuit
   c. Fuel circuit
3. Steam and water circuit composed of:
   a. Steam drum
   b. Mud drum
   c. Downcomers
   d. Risers
4. Feedwater level maintenance is:
   a. Vital to combustion control
   b. Vital to efficient operation
   c. Influenced by swell (occurs during increased steam production) and shrink (occurs during decreased steam production).
5. Steam flow is controlled by demand for steam
   a. Steam pressure is the control impulse for fuel input
6. Flue gas and air circuit
   a. Provides combustion air
   b. Circulates product gases within the furnace
   c. Removes flue gases
7. Furnace draft (negative pressure)
   a. Will be specified in furnace design (some furnaces are pressurized)
   b. Requires proper control of forced draft and induced draft fans.
8. Control of fans for combustion air
   a. Is accomplished by variable dampers or variable speed motors
   b. Must lead fuel-flow increases when load is increased
   c. Must lag fuel-flow when load is decreased
9. Efficiency is increased by use of air preheaters
   a. Tubular type
   b. Regenerative type
10. Control of excess air is required for complete combustion
    a. Too much excess air results in
       i. Less time for heat transfer to the tubes so that the flue gas temperature increases
       ii. More flue gas being emitted at higher temperatures
    b. Greater excess air is required with low load conditions
11. Minimum air flow rate should be limited to 25% of the full load air flow rate
12. Fuel flow controls
    a. Should limit the flow of fuel to the amount of available air
    b. Should provide automatic shut-off valves

13. Only with optimum instrumentation and control can efficiency be maintained under all load conditions.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Combustion Installation Instrumentation

COURSE: 427, Combustion Evaluation
LESSON TIME: 45 min.
PREPARED BY: F. A. Iachetta
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 16

Lesson Goal: The goal of this lesson is to provide the student with information about instruments used for combustion systems monitoring with particular emphasis on good operation.

Lesson Objectives: At the end of this lesson the student will be able to:

identify instruments which would indicate improper combustion or energy transfer; and

describe the influence of excess air (indicated by CO_2 or O_2 in stack gases) on the boiler efficiency, fuel rate, and economics of a particular combustion installation.

Student Prerequisite Skills: Course 427, Lesson 15.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 16

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 6.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 16: COMBUSTION INSTALLATION INSTRUMENTATION
427-16-1	STEAM-FLOW AIR-FLOW METER AND CHART
427-16-2	DRAFT GAUGES ON SPREADER STOKER-FIRED BOILER INSTRUMENT PANEL
427-16-3	GAS AND WATER TEMPERATURES OF ECONOMIZER
427-16-4	INSTRUMENT PANEL WITH REMOTE STACK SMOKE INDICATOR
427-16-5	SKETCH OF REMOTE STACK SMOKE INDICATOR
427-16-6	RANEREX CONTINUOUS CO_2 METER
427-16-7	TYPICAL O_2 READINGS
427-16-8	TYPICAL CO_2 READINGS
427-16-9	EFFECT OF EXCESS AIR (FLUE GAS CO_2) ON COMBUSTION EFFICIENCY
427-16-10	IMPROVED EFFICIENCY CASCADE

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Combustion Installation Instrumentation

Page 3 **of** 4

	NOTES
I. Introduction	
A. State the lesson objectives	
B. Outline the use of instruments as operator guides	
1. Steam-flow air-flow meter on a boiler instrument panel	Slide 427-16-1
a. Note the usual practice of nearly coincident pen traces	
b. Note inherent influence on operator designed into the unit (pens together)	
2. Fuel-flow meter	
a. Used both to guide operator and for recordkeeping	
3. Note draft gauges employed to monitor gas loop components, such as furnace, fans, air preheater, etc.	Slide 427-16-2
4. Temperature measurements	
a. Furnace and flue gases at various points	
b. Gas temperatures at significant locations	Slide 427-16-3
c. Fuel oil where needed	
5. Smoke indicators	Slide 427-16-4
a. Note use of signal lights and opacity indicator scales	Slide 427-16-5
6. CO_2 and O_2 monitoring	Slide 427-16-6
a. Portable and fixed instruments should be described here	
b. Give ranges of CO_2 for several fuels	Slide 427-16-7
c. Give range of O_2 for several fuels	Slide 427-16-8
II. Importance of proper instrumentation relative to efficiency	
A. Describe recordkeeping normally possible	
1. Integrators used on steam-flow, fuel-flow meters, etc.	
a. Note the use of micro-processors to give continuous efficiency estimate	
B. Discuss flue gas monitoring as related to both efficiency and pollutant emissions	
1. Point out efficiency versus CO_2 relationship	Slide 427-16-9
2. Note the effect of flue gas exit temperature on efficiency	
3. Discuss cascade effect of improved efficiency as an argument for flue CO_2 or O_2 gas monitoring instruments	Slide 427-16-10
4. Relate O_2 radiation with efficiency improvement	
a. Note a 1% reduction of O_2 corresponds to 1/2 to 1% improvement of efficiency	
III. Use of Instrumentation in Preventive Maintenance	
A. Outline the preventive maintenance-instrumentation interaction	
1. Note the need for establishing norms as reference values	
2. Describe how instrument reading changes are indicators of problems	

a. Use of CO_2 through unit as measure of air infiltration
b. Temperature variation at preheaters, etc.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Gaseous Fuel Burning

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: L. U. Lilleleht
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 17

Lesson Goal: To provide the student with an accurate understanding of the design and operational parameters which influence the emissions of air pollutants from gas-burning devices.

Lesson Objectives: At the end of this lesson the student will be able to:

describe the functions of the gas burner;

define pre-mix and its influence on the type of flame;

list burner design features and how these affect the limits of stable flame operating region;

name four different types of gas burners and their special design features;

cite typical gas furnace, breeching, and stack operating temperatures, pressures, and gas-flow velocities;

describe the relationship between flue gas analyses and the air-to-fuel ratio;

list the causes and describe the signs of malfunctioning gas-burning devices; and

describe techniques used to correct a malfunctioning gas-burning device.

Student Prerequisite Skills: Course 427, Lessons 2, 3, 5, 6, 9, 15, 16.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 17

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapters 2, 3, and 7.

2. Combustion Handbook, published by the North American Manufacturing Company, Cleveland, Ohio (1952).

3. Danielson, J. A., editor, Air Pollution Engineering Manual, AP-40, 2nd edition, USEPA (May 1973).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 17: GASEOUS FUEL BURNING
427-17-1	BLUE FLAME
427-17-2	YELLOW FLAME
427-17-3	ATMOSPHERIC BURNERS - FLAME STABILITY
427-17-4	ATMOSPHERIC PREMIX TYPE GAS BURNER
427-17-5	MULTI-FUEL OIL GASIFYING BURNER
427-17-6	FURNACE HEAT RELEASE RATE
427-17-7	COMPARITIVE FURNACE SIZES
427-17-8	TYPICAL BREECHING AND STACK CONDITIONS
427-17-9	VELOCITY IN CONVECTIVE SECTION
427-17-10	FLUE GAS ANALYSIS

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Gaseous Fuel Burning

Page 4 of 5

NOTES

- I. Introduction
  - A. State the goals and objectives of this lesson.
  - B. Review combustion concepts
    - 1. Requirements for complete combustion
    - 2. Theoretical and excess air
    - 3. Adequate temperature, turbulence, and time

Refer to Student Manual, Chap. 2

  - C. Typical gaseous fuels
    - 1. Heating values of natural gas and other common gaseous guels
    - 2. Lowest heating value for direct combustion

Refer to Student Manual, Chap. 3, and Lesson No. 6

- II. Flame combustion mechanisms
  - A. Hydroxylation theory
    - 1. Air mixes with fuel prior to combustion
    - 2. Oxidation is gradual
    - 3. Blue flame is produced
    - 4. Incomplete combustion products include:
      - a. Aldehydes and acrid odor
      - b. Other partially-oxidized hydrocarbons

Slide 427-17-1

  - B. Carbonic combustion mechanism
    - 1. Fuel is not premixed with air
    - 2. Cracking reaction produces solid carbon
    - 3. Yellow flame from incandescent carbon
    - 4. Incomplete conbustion products include soot, smoke, carbon monoxide, etc.

Slide 427-17-2

- III. Gas-burning characteristics
  - A. Functions of a gas burner
    - 1. To deliver gas and air at the desired rate and proportion
    - 2. To provide mixing and ignition.
  - B. Most burners employ the Bunsen principle
    - 1. Some (primary) air is premixed
    - 2. Remainder is secondary air
    - 3. Flame propagation velocity
    - 4. Shape and appearance of flames affected by
      - a. Degree of pre-mix
      - b. Degree of turbulence and mixing

Refer to Student Manual, p. 7-19.
Refer to Student Manual, p. 7-18.

  - C. Stable flame region
    - 1. Bounded by
      - a. Flash-back
      - b. Lifting and blow-off
      - c. Yellow tip
      - d. CO formation
    - 2. Turn-down ratio

Slide 427-17-3
Refer to Student Manual, p. 7-20.

- IV. Classification of gas burners
  - A. Pre-mix type
    - 1. Atmospheric burners
    - 2. Multiple port burners
    - 3. Power burners
  - B. Nozzle-mixing type
  - C. Long flame burners
  - D. Specialty gas burners:

Slide 427-17-4
Refer ro Student Manual, p. 7-17 and 7-21.

1. High excess air burners to provide hot gases at uniform temperature
2. Lean fuel burners for very low heating value fuels

Slide 427-17-5
Refer to Student Manual, p. 7-24.

3. Multi-fuel burners
4. Other

V. System design considerations
A. Combustion furnace volume
1. Flame to fill volume
2. Shape determined by type and number of burners
B. Typical energy release rates
1. In primary zone and overall

Slide 427-17-6

2. Comparison with other fuels

Slide 427-17-7

C. Furnace operating conditions
1. Pressure slightly lower than ambient
2. Velocities in convective section

Slide 427-17-8

D. Breeching and stack
1. Draft control
a. Natural
b. Forced and/or induced
2. Stack conditions

Slide 427-17-9

a. Typical flow rate (velocity)
b. Temperature
(i) Effect on heat losses
(ii) Minimum required to prevent condensation

VI. Operation and Control
A. Control of air-to-fuel ratio
1. Flue gas analysis

Slide 427-17-10
Refer to Student Manual, pp. 7-25 and 7-26.

2. Flame appearance and temperature
3. Burner nozzle adjustment
B. Evidence of insufficient air
C. Evidence of too much excess air
D. Safety considerations:
1. Start-up and shut-down procedures
2. Fuel changes should not be attempted without prior thorough analysis by experts.

VII. Air pollution considerations
A. Most gaseous fuels are clean burning in properly designed, operated, and maintained equipment
B. Pollutant emissions from:
1. Operating outside stable flame region
2. Insufficient air
3. Improper operation of burner:
a. Damaged by flash-back
b. Throat clogged by soot
4. Inadequate mixing
5. Excessive firing rate for given design
C. Uncontrolled emissions factors from gas-burning devices

Refer to Student Manual, Attachments 7-11, 7-12.

1. Natural gas
2. Liquefied petroleum gas (LPG).

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Fuel Oil Burning

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: J. T. Beard
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 18

Lesson Goal: The goal of this lesson is to provide the student with an accurate understanding of the design and operational parameters which influence air pollution emissions from fuel oil burning equipment.

Lesson Objectives: At the end of this lesson the student will be able to:

describe the important design and emission characteristics of oil burners using air, steam, mechanical (pressure) and rotary cup atomization;

describe the influence of temperature on oil viscosity and atomization;

describe how vanadium and sulfur content in fuel oil influence furnace corrosion and air pollution emissions;

describe burner nozzle maintenance and its influence on air pollutant emissions from oil combustion installations; and

locate and use tabulated values of oil fuel properties and pollutant factors to compute uncontrolled emissions from oil-burning sources.

Student Prerequisite Skills: Course No. 427, Lessons Number 6, 9, 15, 16

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 18.

Special Instructions: None

References:

1. *Combustion Evaluation in Air Pollution Control*, Chapter 8.
2. "Guidelines for Residential Oil Burner Adjustment," EPA-600/2-75-069a (Oct. 1975).
3. "Guidelines for Burner Adjustments of Commercial Oil-Fired Boilers," EPA-600/2-76/008, published by Industrial Env. Res. Lab., USEPA (March 1976).
4. "Guidelines for Industrial Boiler Performance Improvement," EPA-600/8-77-003a, published by Industrial Env. Res. Lab., USEPA (Jan. 1977).
5. Burkhardt, C. H., *Domestic and Commercial Oil Burners*, Third Edition, McGraw-Hill Book Co., New York (1969).
6. Fryling, G. R., *Combustion Engineering*, Revised Edition, published by Combustion Engineering, Inc. New York (1966).
7. *Steam: Its Generation and Use*, 38th Edition, published by Babcock and Wilcox, New York (1972).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 18: FUEL OIL BURNING
427-18-1	PURPOSE OF FUEL OIL BURNING
427-18-2	REQUIREMENTS FOR COMPLETE COMBUSTION
427-18-3	MODE OF COMBUSTION OF FUEL OIL DROPLETS
427-18-4	APPROXIMATE VISCOSITY OF FUEL OILS
427-18-5	TYPICAL EXCESS AIR LEVELS
427-18-6	VOLUMETRIC HEAT RELEASE RATES AND RESIDENCE TIMES
427-18-7	SCOTCH-MARINE BOILER
427-18-8	INTEGRAL FURNACE BOILER
427-18-9	WATER WALL TUBES
427-18-10	WATER WALL TUBES
427-18-11	INTEGRAL FURNACE BOILER, TYPE D
427-18-12	VERTICALLY-FIRED OIL BURNING FURNACE
427-18-13	TEMPERATURES IN BOILER OF PREVIOUS SLIDE
427-18-14	BOILER, TANGENTIALLY FIRED
427-18-15	WATER-WALL FURNACE CROSS SECTION (TANGENTIALLY FIRED)
427-18-16	ATOMIZING CHARACTERISTICS OF DIFFERENT BURNERS
427-18-17	ROTARY CUP BURNER
427-18-18	HIGH-PRESSURE ATOMIZER (DOMESTIC)
427-18-19	LOW-PRESSURE AIR ATOMIZER
427-18-20	LOW-PRESSURE AIR ATOMIZER SKETCH
427-18-21	LOW-PRESSURE AIR ATOMIZER MOUNTED IN COMMERCIAL FURNACE
427-18-22	TANGENTIAL SWIRL NOZZLES
427-18-23	SWIRL DEVICE FOR SECONDARY AIR
427-18-24	HIGH-PRESSURE ATOMIZER

SLIDE NUMBER	TITLE OF SLIDE
427-18-25	MECHANICAL ATOMIZATION (WITH RETURN FLOW, SPILL BACK)
427-18-26	EXAMPLES OF RETURN FLOW HIGH AND LOW FIRE
427-18-27	STEAM ATOMIZING (INTERNAL MIX)
427-18-28	STEAM ATOMIZING (INTERNAL MIX)
427-18-29	INTERNAL MIX STEAM ATOMIZING NOZZLE
427-18-30	INTERNAL MIX STEAM ATOMIZING NOZZLE
427-18-31	INTERNAL MIX STEAM ATOMIZING NOZZLE
427-18-32	STEAM OR AIR ATOMIZING BURNER (EXTERNAL MIX)
427-18-33	INFLUENCE OF DRAFT - CASE HISTORY
427-18-34	SMOKE - CO_2 CHARACTERISTICS

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Fuel Oil Burning

NOTES

- I. Introduction
  - A. State the lesson objectives
  - B. Introduce fuel burning concepts
    - 1. State the purpose (production of hot gases) — Slide 427-18-1
    - 2. Discuss desirable features
      - a. Burning the fuel completely
      - b. Using a minimum quantity of air
      - c. Discarding the flue gas at a reasonably low temperature
    - 3. State requirements for proper combustion — Slide 427-18-2
      - a. Fine atomization (vaporization)
      - b. Good mixing with air (turbulence)
      - c. Continuous source of ignition (temperature)
      - d. Time to complete combustion
      - e. No quenching of gases until combustion is complete
  - C. Review and give examples of important fuel properties
    - 1. Vaporization limits combustion rate
      - a. Kerosene
      - b. No. 6 fuel oil
    - 2. Contrast chemical and physical behavior of distillate and residual oil droplet — Slide 427-18-3
      - a. Distillation, thermal, and catalytic cracking
      - b. Physical size changes with time
      - c. Possible residue
    - 3. Define viscosity, cite variations, and give related design examples — Slide 427-18-4
      - a. No preheating for No. 2
      - b. Preheating to 135° for atomizing No. 4
      - c. Preheating to 185° for atomizing No. 5
      - d. Preheating to around 210° for pumping and atomizing No. 6
    - 4. Cite examples of nozzle problems caused by foreign matter in oil
      - a. Strainers required in the oil suction and discharge lines
      - b. Small size burners may have fine mesh screen or porous plug type filters
      - c. Some systems mechanically reduce particle sizes to allow flow through the pump, filter, and nozzle
- II. Describe furnace sizes, applications, and distinguishing features, such as heat release rate and residence time — Slide 427-18-5, Slide 427-18-6
  - A. Domestic or Residential
    - 1. No. 1 or No. 2 fuel oil, ½ to 3 gph
    - 2. Around 40% excess air
    - 3. Simple on/off combustion control
    - 4. Annual nozzle maintenance
  - B. Commercial
    - 1. Present, as examples, Scotch marine, HRT (horizontal return fire tube), and integral furnace water-wall boilers — Slide 427-18-7, Slide 427-18-8, Slide 427-18-9, Slide 427-18-10

	NOTES
2. No. 2, 4, 5, 6 fuel oil, 3 to 100 gph	
3. Around 30% excess air	
4. Standard designed package heaters and boilers	
5. Typically use electric heating of oil	
C. Industrial	
1. Present, as an example, an integral furnace boiler (D-type)	Slide 427-18-11
2. Large special-purpose heaters and boilers	
3. No. 4, 5, 6 fuel oil, 70 to 3,500 gph	
4. Around 15% excess air	
D. Utility	
1. Describe features of radiant boilers with vertical, horizontal, and tangential firing.	Slides 427-18-12, 13 Slide 427-18-14
2. Sophisticated combustion controls and monitors	Slide 427-18-15
3. Steam production at high efficiency	
4. No. 6 fuel oil, 3,500 to 60,000 gph	
5. Around 3% excess air	
III. Describe the design and operational features of example burners as related to	
A. Atomization size distribution	Slide 427-18-16
1. Rotary cup burner produces large droplets, not recommended because of poor combustion features	Slide 427-18-17
B. Fuel and furnace application	
1. High-pressure atomizers for domestic or residential applications	Slide 427-18-18
a. Pressure of 100 psi	
b. No. 2 fuel oil, ½ to 30 gph	
c. Swirl vanes to provide mixing by secondary air	
d. Electrodes provide continuous source of ignition	
2. Low-pressure air atomizers for domestic applications	Slide 427-18-19
a. Oil and air pressure around 3 psi	
b. No. 2 fuel oil, ½ to 6 gph	
c. Tangential air passages for swirl of primary air prior to impacting film of oil	
3. Low-pressure air atomizers for commercial applications	Slide 427-18-20 Slide 427-18-21
a. Air and oil pressure from 12 to 50 psi	
b. No. 2, 4, or 5 fuel oil, 5 to 150 gph	
c. Describe tangential swirl nozzles	Slide 427-18-22
d. Describe swirl for secondary air	Slide 427-18-23
4. High-pressure atomizers for commercial, industrial applications	Slide 427-18-25 Slide 427-18-26
a. Oil pressure at up to 300 psi	
b. No. 4 or 5 fuel oil, up to 200 gph	
5. Mechanical atomizer for industrial or utility applications	Slide 427-18-27 Slide 427-18-28
a. Oil pressure 450 to 1,000 psi	
b. No. 6 fuel oil rated up to 1,250 gph	
c. Spill-back pressure adjustment for modulated firing	

6. Steam (or air) atomizers for industrial or utility applications
    a. Oil pressure up to 100 psi and steam pressure 20 to 40 psi greater than oil
    b. No. 6 fuel oil, rated up to 1,100 gph
    c. Internal mix, desirable flame
    d. External mix, not recommended due to hot, short flame
    e. Steam trap required to assure dry steam and limit erosion of nozzle

Slide 427-18-29
Slide 427-18-30
Slide 427-18-31
Slide 427-18-32

IV. Factors Influencing Air Pollutants
  A. Present emission factors for fuel oil combustion

Refer to Student Manual, p. 8-16

    1. Describe variations in particulate emission factors
        a. Vary with fuel type because more ash in heavier oils
        b. For No. 6, asphaltine content may burn poorly and varies with sulfur content
    2. Describe why emission factor coefficient for SO_2 is larger for residual oil than for distillate
        a. Factor based on oil volume rather than weight therefore higher density gives higher coefficient
    3. Explain variations in NO_x emission factors
        a. Fuel nitrogen
        b. Equipment design influences to be presented in later lesson
    4. Provide sample calculation of use of emission factor
        a. Point out that S in emission factor for 0.7% sulfur fuel is 0.7, not 0.007.
  B. Describe influence of vanadium content in fuel oil (also coal)
    1. Deposited in ash on metallic surfaces
        a. Acts as catalyst for conversion of SO_2 to SO_3
        b. Dew point problems (acid smuts, corrosion)
        c. Low excess air also limits conversion to SO_3 and acid smut emissions
        d. Some SO_3 desirable for electrostatic precipitator operation
    2. Switching to low vanadium fuel may be possible
    3. Vanadium and sodium form
        a. Sticky, low melting temp ash deposits
        b. Increase fouling of metal surfaces
        c. Corrosive
  C. Describe soot blowing
    1. Less of soot with oil than with coal
    2. Frequency
        a. Avoid buildup to maintain heat transfer
        b. Keep ash from becoming molten (hard to remove)
        c. More frequent with vanadium and sodium in oil
  D. Describe influence of fuel oil additives
    1. Alumina, dolomite, magnesia
        a. Reduce superheater fouling, ash corrosion

    b. May produce high melting point ash deposits
    c. May form refractory sulfates in ash, removed in soot blowing
  2. Organometallic compounds of
    a. Transition metals (manganese, iron, nickel, and cobalt)
    b. Alkaline-earth metals (barium and calcium)
  3. Catalytic influences to reduce smoke and particulates
    a. Oxidation of soot
    b. Promotion of free radicals which react with soot
E. Describe nozzle maintenance
  1. Remove, check for deposits, cracks, wear, plugging
  2. Clean deposits or replace
  3. Frequency depends on installation
    a. Once a shift for industrial and utility boilers
    b. Once a year for residential burners
  4. Poor atomization
    a. Changed atomization pattern
    b. Larger droplet sizes
    c. Longer flames with increased soot or slag
F. Describe continuous ignition requirements
  1. Continuous spark from electrodes in domestic units
    a. 7,000 to 10,000 volt transformer
    b. Proper positioning required in maintenance
  2. Utility and industrial units typical programmed starting sequence
    a. Pilot for start-up on gas or distillate oil
    b. Auxiliary fuel during cold start to prevent smoke
    c. Modulated burner controls
    d. Safety interlocks
    e. Optical, pressure, or temp. sensing equipment
G. Define draft and describe its importance for good combustion — Slide 427-18-33
  1. Negative pressure difference between furnace or stack and ambient
  2. Control required to assure
    a. Velocities (residence time)
    b. Air/fuel mixing
    c. Settling for blown soot
  3. Give example of too much furnace draft
    a. Inadequate residence time
  4. Give example of too low stack draft
    a. Inadequate pressure drop to pull gases across convective section
  5. Give example of negative draft
    a. Furnace pressure greater than atmospheric
    b. Gases leak out (rather than in) may cause quenching (smoke) and structural damage due to overheating
    c. Gasing of operating personnel
  6. Introduce the EPA recommended CO_2/smoke adjustment procedure to be presented in later lesson — Slide 427-18-34

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Film — "Combustion for Control of Gaseous Pollutants

COURSE: 427, Combustion Evaluation
LESSON TIME: 30 min.
PREPARED BY: L. U. Lilleleht
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 19

Lesson Goal: To review and reinforce the student's understanding of the fundamental combustion concepts in controlling gaseous pollutants through direct-flame or catalytic incineration and by flares.

Lesson Objectives: At the end of this film the student will be able to:

list the four items necessary for effective disposal of gaseous pollutants by combustion;

give the limit(s) on pollutant concentrations for direct-flame and catalytic incinerators and cite reasons for such limit(s);

compare the major advantages and disadvantages of catalytic incinerators over direct-flame incinerators;

outline the operating principles of a flare; and

list the conditions under which a flare can be used for disposal of combustible gases.

Student Prerequisite Skills: First-level college chemistry.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Film — "Combustion for Control of Gaseous Pollutants"
2. 16-mm sound movie projector with a 12-inch diameter take-up reel.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 13.
2. APTI Course #415: Control of Gaseous Emissions.

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Film — "Combustion for Control of Gaseous Pollutants"

Page 3 *of* 3

NOTES

I. Introduction
   A. This film will serve as an introduction to the control of gaseous pollutants by combustion. It will also be a brief refresher for those students who have already had Course #415, Control of Gaseous Emissions.
   B. The film presents the fundamental concepts of direct-flame incineration, catalytic incineration, and flares.
   C. Operating principles are explained schematically, followed by illustrations of actual hardware.
   D. The student is also introduced to the concept of energy conservation through the use of heat recovery.
II. "Combustion for Control of Gaseous Pollutants"
III. Discussion of comments and questions raised by viewers.

Film: "Combustion for Control of Gaseous Pollutants"

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Direct-Flame and Catalytic Incineration

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: L. U. Lilleleht
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 20

Lesson Goals: To provide the student with an understanding of the combustion techniques available for controlling gaseous and volatile organic pollutants and with design bases for thermal or catalytic afterburners.

Lesson Objectives: At the end of this lesson the student will be able to:

cite examples of air pollution sources where direct-flame and catalytic afterburners are used to control gaseous emissions;

describe the influence of temperature on the residence time required for proper operation of afterburners;

apply fundamental combustion calculations to determine the auxiliary fuel required for direct-flame and catalytic incineration with and without energy recovery;

list three reasons for loss of catalytic activity and ways of preventing such loss; and

cite methods available for reducing afterburner operating costs.

Student Prerequisite Skills: Course 427, Lessons 2, 3, 5, 6, 17

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 20

Special Instructions: None

References:

1. *Combustion Evaluation in Air Pollution Control*, Chapters 2, 7, 13.

2. Edwards, J. B., *Combustion — The Formation and Emission of Trace Species*, Ann Arbor Science Publishers, Ann Arbor, Michigan (1974).

3. "Control of Volatile Organic Emissions from Existing Stationary Sources," Vol. I, USEPA Report No. EPA-450/2-76-028 (Nov. 1976).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 20: DIRECT FLAME AND CATALYTIC INCINERATION
427-20-1	CONTROL OF OBJECTIONABLE GASES AND VAPORS
427-20-2	COMBUSTION EQUIPMENT
427-20-3	DIRECT FLAME OXIDATION
427-20-4	COUPLED EFFECTS OF TEMPERATURE AND TIME ON HYDROCARBON OXIDATION RATE
427-20-5	TYPICAL THERMAL AFTERBURNER EFFECTIVENESS FOR HYDROCARBON AND CARBON MONOXIDE MIXTURES
427-20-6	INDUCED DRAFT FUME INCINERATOR
427-20-7	DIRECT-FLAME AFTERBURNER
427-20-8	CATALYTIC AFTERBURNER SCHEMATIC
427-20-9	OXIDATION TEMPERATURE
427-20-10	INDUSTRIAL APPLICATIONS OF CATALYTIC COMBUSTION
427-20-11	TYPICAL CATALYSTS AND THEIR SUPPORTS
427-20-12	LOSS OF CATALYST ACTIVITY
427-20-13	CATALYTIC INCINERATOR WITH RECYCLE AND HEAT ECONOMIZER
427-20-14	CERAMIC BED REGENERATIVE-TYPE INCINERATOR AND HEAT RECOVERY SYSTEM

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Direct-Flame and Catalytic Incineration

NOTES

- I. Introduction
  - A. State the goals and objectives of this lesson
  - B. Outline the need for controlling gaseous and aerosol wastes
    - 1. Precursors for atmospheric oxidants
    - 2. Economics
  - C. Mention sources of emissions of volatile organic compounds (VOC)
  - D. Discuss VOC control strategy:
    - 1. Substitution of solvents
    - 2. Process and material changes
    - 3. Add-on control devices
  - E. Enumerate VOC control methods: — Slide 427-20-1
    - 1. Absorption
    - 2. Adsorption
    - 3. Incineration
      - a. Thermal
      - b. Catalytic
    - 4. Chemical conversion — Slide 427-20-2
  - F. Describe gaseous and aerosol waste incineration equipment
- II. Direct-Flame and Furnace Incineration
  - A. Consider the oxidation reaction — Slide 427-20-3
    - 1. Gases at less than 25% LEL — Slide 427-20-4 or refer to Student Manual, p. 13-17.
    - 2. Time-temperature relation
      - a. For hydrocarbons
      - b. For hydrocarbon and carbon monoxide mixtures — Slide 427-20-5 or refer to Student Manual, p. 13-18.
  - B. Discuss the use of existing process heaters
    - 1. Requirements for use
  - C. Describe thermal incineration — afterburners — Slide 427-20-6
    - 1. Typical design bases:
      - a. Temperature — 1,200-1,500°F
      - b. Time — 0.3 to 0.6 sec.
      - c. Mixing (turbulence)
    - 2. Auxiliary fuel burner
      - a. Source of combustion air
        - (i) Waste gas
        - (ii) Fresh outside air
      - b. Fuel requirement
        - (i) Hypothetical available heat calculations
      - c. Mixing of combustion products with the waste gases
        - (i) Arrangement of burners
        - (ii) Baffles
        - (iii) Velocity for good mixing
    - 3. Furnace chamber design parameters — Slide 427-20-7 or refer to Student Manual, p. 13-8.
      - a. Velocity of gases
      - b. Shape — L/D greater than 2
      - c. Material of construction
        - (i) Choice dictated by temperature
- III. Catalytic Incineration — Slide 427-20-8 or refer to Student Manual, p. 13-28.
  - A. Present principles of operation

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Direct-Flame and Catalytic Incineration

NOTES

1. Mechanisms of catalytic activity
    a. Reaction at lower temperature
        (i) Compare with furnace incinerators
        (ii) Less auxiliary fuel
        (iii) Less expensive materials of construction

B. Describe typical oxidation catalysts
    1. Materials
    2. Loss of catalytic activity from:
        a. Poisons
        b. Suppressants
        c. Fouling

C. Discuss operational requirements
    1. Typical equipment arrangement
    2. Combustibles at less than 25% LEL
    3. No particulates
    4. Hot start-up to avoid carbon deposits

IV. Methods for Reducing Afterburner Operating Costs
    A. Consider eliminating or reducing separate combustion air intake
        1. With waste containing 16% or more oxygen
        2. Hypothetical available heat calculations
    B. Mention the use of heat-recovery devices
        1. Regenerative systems
        2. Recuperative systems
        3. Reported range of heat recovery
        4. Actual energy savings
    C. Discuss the burning of combustible waste liquids
    D. Propose using incinerator exhaust as a source of heated inert gas for dryers, etc.

Refer to Student Manual, Chapter 2, and Lesson No. 5. Slides 427-20-9, 427-20-10.

Slide 427-20-11
Slide 427-20-12

Slide 427-20-13 or refer to Student Manual, p. 13-9.

Slide 427-20-14 or refer to Student Manual, p. 13-10.

Refer to Student Manual, Attachment 13-4, p.13-11.

Refer to Student Manual, p. 13-12.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Problem Session V:
Afterburner Design

COURSE: 427, Combustion Evaluation
LESSON TIME: 45 min.
PREPARED BY: L. U. Lilleleht
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 21

Lesson Goal: To provide the students with experience in calculating the auxiliary fuel requirements for an afterburner installation and to develop an appreciation for the design bases and parameters.

Lesson Objectives: At the end of this lesson the student will be able to:

determine auxiliary fuel requirements with separate fresh combustion air intake;

estimate the volumetric flow rate of gases through the afterburner at the specified incineration temperature;

determine the dimensions of the afterburner to achieve the necessary level of mixing and effluent residence time; and

perform the above calculations without fresh combustion air intake but using instead the oxygen in the contaminated stream for combustion.

Student Prerequisite Skills: Course No. 427, Lessons 2, 3, 17, 19, 20

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Blackboard and chalk or an overhead projector with transparency material and pens.
2. Workbook for Combustion Evaluation in Air Pollution Control, Chapter V.
3. Hand-held calculator or slide rule.

Special Instructions: Assign Problem V.2 for homework.

References:

1. Combustion Evaluation in Air Pollution Control, Chapters 2 and 13.

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Problem Session V: Afterburner Design

NOTES

I. Introduction
   A. State the goals and objectives of this lesson.

II. Problem V.1: Afterburner Design for Meat Smokehouse Effluent
   A. Present the problem statement and solution (by instructor): Consider a meat smokehouse discharging 1,000 scfm effluent at 150°F, which needs to be treated to control a very low concentration of pollutants at the parts-per-million level. This could be accomplished by thermal incineration at 1,200°F for at least 0.3 seconds.
   Determine:
      1. The natural gas required for preheating the contaminated effluent to 1,200°F using all fresh combustion air intake.
      2. The afterburner throat diameter to give 20 ft/sec throat velocity for good mixing.
      3. The diameter and the length of the afterburner for a minimum L/D ratio of 2 and afterburner chamber velocity of 12 ft/sec.
   B. Present the reasonable assumptions:
      1. The amount of combustibles in effluent gases is very low; there is no contribution to the heating value due to their oxidation.
      2. Effluent gases have the same thermal properties as air.
      3. Intake combustion air is available at 60°F.
   C. Choose a basis for calculation.
   D. Determine the mass flow rate of effluent
   E. Estimate the heat required to raise effluent temperature to 1,200°F.
   F. Determine the amount of natural gas required.
   G. Compute combustion products and effluent volume at 1,200°F.
   H. Determine afterburner throat diameter.
   I. Determine incinerator chamber diameter and length.
   J. Check the residence time.
   K. Discuss other design options:
      1. Reduced auxiliary fuel by using oxygen from effluent stream.
      2. Heat recovery from clean afterburner effluent.

III. Outline procedure for calculating hypothetical available heat.

Refer to Student Manual, Reference 7-1.

IV. Problem V.2: Afterburner Design with Combustion Oxygen from the Contaminated Effluent
   A. Assign this problem for homework.
   B. Present the problem statement:
   Assume that the meat smokehouse effluent in Problem V.1 has also the same composition as air (21% by volume oxygen) except for the minute concentration of contaminants. Repeat the calculations of Problem V.1, but use the oxygen from the smokehouse effluent for combustion of the auxiliary fuel as much as possible.

Determine:

1. The hypothetical available heat for this afterburner application.
2. The natural gas requirements and the fraction of combustion oxygen available from the effluent.
3. The afterburner dimensions as in Problem V.1-3.

C. State other assumptions: A mixing-plate type burner (see Attachment 7-6) will be used in this application. A ring baffle, which was used in Problem V.1, will therefore not be necessary to obtain good mixing between the auxiliary fuel combustion products and the effluent to be incinerated.

D. Outline problem solution

1. Discuss choice of burner and type of afterburner hardware
2. Describe how to determine auxiliary fuel requirements, including the calculation procedures to be used for "hypothetical available heat."
3. Answers to Problem V.2 are to be confirmed during the Homework Review period.

Refer to Student Manual, Attachment 7-6, p.7-22.

Refer to Student Manual, Reference 7-1, and Student Workbook, Chapter V, Problem V.2.

CHAPTER V

AFTERBURNER DESIGN PROBLEMS

PROBLEM V.1: Afterburner Design for Meat Smokehouse Effluent

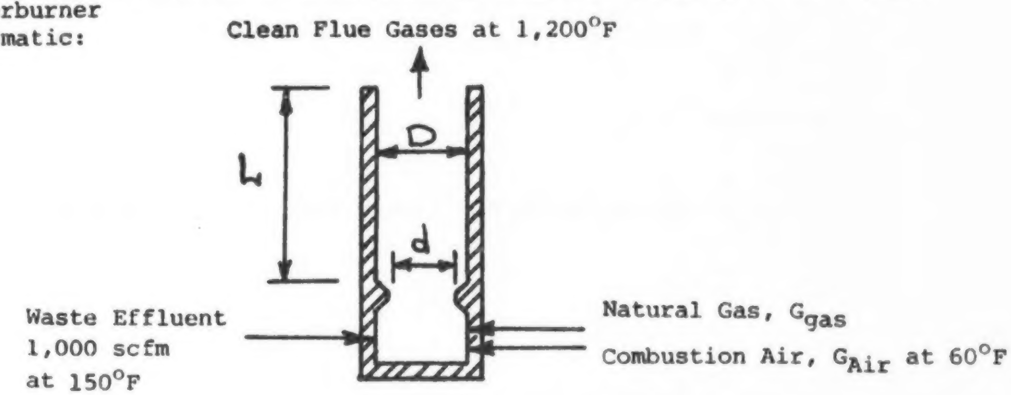
Consider a meat smokehouse discharging 1,000 scfm effluent at 150°F, which needs to be treated to control a very low concentration of pollutants at the parts-per-million level. This could be accomplished by thermal incineration at 1,200°F for at least 0.3 seconds. The following are reasonable assumptions:

1. The amount of combustibles in effluent gases is very low; there is no contribution to the heating value due to their oxidation.
2. Effluent gases have the same thermal properties as air.
3. Intake combustion air is available at 60°F.

Determine:

1. The natural gas required for preheating the contaminated effluent to 1,200°F using all fresh combustion air intake.
2. The afterburner throat diameter to give 20 ft/sec throat velocity for good mixing.
3. The diameter and the length of the afterburner for a minimum L/D ratio of 2 and afterburner chamber velocity of 12 ft/sec.

Afterburner
Schematic:


Clean Flue Gases at 1,200°F
L
D
d
Waste Effluent
1,000 scfm
at 150°F
Natural Gas, G_{gas}
Combustion Air, G_{Air} at 60°F

Solution to Problem V.1:

Choose as a basis for calculation:

1 hour operation

Part 1.

a. Calculate waste effluent flow rate, $\dot{m}$ (lb/hr)

$$\dot{m} = \text{(volume flow rate) (density)}$$

Since assumed effluent to have properties of air, density from Attachment 2-1, p. 2-23 of the Student Manual.

$$\dot{m} = \text{(1,000 scfm) (0.0766 lb/scf) (60 min/hr)} = \text{4,600 lb/hr}$$

b. Calculate the heat required to increase the effluent waste stream temperature from 150°F to 1,200°F, allowing for 10% loss (i.e., multiply by 1.10):

$$Q = 1.10\ \dot{m}\ \Delta H$$

Enthalpy difference, ΔH, obtained by using Attachment 2-7, p. 2-29 of the Student Manual:

Enthalpy of air at 1,200°F is: 288.5 Btu/lb

Enthalpy of air at 150°F is: 21.6 Btu/lb

Therefore, ΔH = 266.9 Btu/lb

Therefore,

$$Q = \text{(1.10) (4,600 lb/hr) (266.9 Btu/lb)} = 1.35 \times 10^6 \text{ Btu/hr.}$$

c. Available heat from natural gas, Q_A (Btu/scf)

Assume: Gross heating value of natural gas = 1,059 Btu/scf

Theoretical combustion air = 10.0 scf air/scf gas

Combustion products = 11.1 scf/scf gas.

From Attachment 2-9, p. 2-31 of the Student Manual, obtain for 1,200°F flue gas temperature:

$$Q_A = 690 \text{ Btu/scf}$$

(This is the amount of heat remaining after the combustion products from 1 scf of gas are raised to the afterburner temperature. This heat is then available for heating the waste effluent to the same afterburner temperature.)

d. Natural gas needed, G_{gas} (scfh):

$$G_{gas} = (1.35 \times 10^6 \text{ Btu/hr})/(690 \text{ Btu/scf gas}) = 1,960 \text{ scf gas/hr.}$$

Part 2.

a. Volume of combustion products at 1,200°F, G_p (ft^3/sec):

$$G_P = (1,960 \text{ scf gas/hr})(11.0 \text{ scf prod/scf gas})(460 + 1,200,^\circ R)/(460 + 60,^\circ R)$$

$$= 68,800 \text{ ft}^3\text{/hr} = 19.1 \text{ ft}^3\text{/sec.}$$

b. Volume of waste effluent at 1,200°F, G_E (ft^3/sec)

$$G_E = (1,000 \text{ scfm})(460 + 1,200,^\circ R)/(460 + 60,^\circ R)$$

$$= 3,190 \text{ ft}^3\text{/min} = 53.2 \text{ ft}^3\text{/sec.}$$

c. Total volumetric flow of gases to the afterburner chamber through the throat:

$$G_{tot} = G_p + G_E = 19.1 + 53.2 = 72.3 \text{ ft}^3\text{/sec.}$$

(V-3)

d. Afterburner throat area $A_{throat} = \pi d^2/4$

Throat diameter $d = (4A_{throat}/\pi)^{\frac{1}{2}}$ (A

Now the velocity through the throat is:

$V_{throat} = G_{tot}/A_{throat}$ (B

Combining Equations (A) and (B) above to eliminate the throat area and solving for throat diameter, d :

$$d = \left[\frac{4\ G_{tot}}{\pi\ V_{throat}}\right]^{\frac{1}{2}} \qquad \text{(C)}$$

For required throat velocity of 20 ft/sec:

$$d = \left[(4/\pi)\ (72.3\ ft^3/sec)\ /\ (20\ ft/sec)\right]^{\frac{1}{2}} = \underline{\underline{2.15\ ft}}$$

Part 3.

Afterburner chamber velocity specified at 12 ft/sec. Thus chamber diameter, D, obtained from Equation (C) above with V_{throat} replaced by $V_{chamber}$ = 12 ft/sec

$$D = \left[(4/\pi)\ (72.3\ ft^3/sec)\ /\ (12\ ft/sec)\right]^{\frac{1}{2}} = \underline{\underline{2.77\ ft}}$$

Length of afterburner chamber ($L/D \geq 2$)

Minimum $L = 2D = (2)\ (2.77) = 5.54$ ft (D)

Check residence time, t

$t = L/V_{chamber} = (5.54\ ft)\ /\ (12\ ft/sec) = 0.46$ sec (E)

Since t = 0.46 sec is greater than the minimum required residence time of 0.30 sec, the above design is satisfactory.

Note: Natural gas requirements can be reduced by:

(i) heat recovery from clean gases to preheat incoming waste effluent, and

(ii) using oxygen from the waste effluent stream for combustion, thereby reducing primary air requirements for the auxiliary fuel.

This latter option is illustrated in Problem V.2.

PROBLEM V.2: Afterburner Design with Combustion Oxygen from the Contaminated Effluent

Assume that the meat smokehouse effluent in Problem V.1 has also the same composition as air (21% by volume oxygen) except for the minute concentration of contaminants. Repeat the calculations of Problem V.1, but use the oxygen from the smokehouse effluent for combustion of the auxiliary fuel as much as possible.

Reasonable assumptions are: a mixing-plate type burner (see Attachment 7-6) will be used in this application. A ring baffle, which was used in Problem V.1, will therefore not be necessary to obtain good mixing between the auxiliary fuel combustion products and the effluent to be incinerated.

Determine:

1. The hypothetical available heat for this afterburner application.
2. The natural gas requirements and the fraction of combustion oxygen available from the effluent.
3. The afterburner dimensions as in Problem V.1-3.

Solution to Problem V.2:

Preliminary Notes on Hypothetical Available Heat Calculations:

Let X = fraction of theoretical air for burning auxiliary fuel entering through the burner (primary or fresh intake air)

$1 - X$ = fraction of theoretical air from waste effluent

H_E = heat content (enthalpy) of effluent at final temperature

$$H_E = C_p \, \Delta T = (0.24 \text{ Btu/lb-}^\circ\text{F})(T - 60, {}^\circ\text{F}) \qquad \text{(A)}$$

W = weight of combustion air from effluent

$$W = (A_{Th})(1 - X)\, \rho_{Air} \qquad \text{(B)}$$

Heat content, Q, of that combustion air at final afterburner temperature

$$Q = W H_E = A_{Th} (1 - X) \rho H_E \tag{C}$$

Since this amount of heat, Q, is no longer needed to heat up fresh intake (primary) air, it will be available to heat the rest of the contaminated effluent. Thus we have a "hypothetical" available heat, Q'_A:

$$Q'_A = Q_A + Q \tag{D}$$

$$Q'_A = Q_A + A_{Th} (1 - X) \rho H_E \tag{E}$$

where Q_A obtained from sources such as Attachment 2-9, p. 2-31 of the Student Manual

ρ = 0.0766 lb air/scf

A_{Th} = 10.0 scf air/scf natural gas burned (typically)

H_E = calculated from Equation (A)

For a natural gas with 1,059 Btu/scf gross heating value and the above burning characteristics, the hypothetical available heat as a function of the afterburner temperature is:

Afterburner Temperature °F	Hypothetical Available Heat Q'_A, Btu/scf gas
600	830 + 100 (1 - X)
800	785 + 136 (1 - X)
1,000	740 + 173 (1 - X)
1,200	690 + 210 (1 - X)
1,400	645 + 246 (1 - X)
1,600	600 + 283 (1 - X)
1,800	550 + 320 (1 - X)

Part 1.

Assume first that no primary air is needed, i.e. $X = 0$, and all combustion air comes from the waste effluent. This needs to be checked; if assumption is not justified, adjust value of X and go through the calculations again.

Hypothetical available heat for $T = 1{,}200^{o}F$:

$$Q'_A = \underline{690} + \underline{210} \ (1 - 0) = \underline{900} \text{ Btu/scf gas}$$

Part 2.

Auxiliary natural gas fuel needed

$$G_{gas} = (\text{Heat to raise effluent to } 1{,}200^{o}F)/Q'_A$$

$$= (1.35 \times 10^6 \text{ Btu/hr})/(\underline{900} \text{ Btu/scf gas})$$

$$= \underline{1{,}500} \text{ scf gas/hr}$$

Theoretical air needed to burn auxiliary gas:

$$G_{air} = (G_{gas})\ (A_{Th})$$

$$= (\underline{1{,}500} \text{ scf gas/hr})\ (10.0 \text{ scf air/scf gas})/(60 \text{ min/hr})$$

$$= \underline{250} \text{ scfm air.}$$

Compare the above G_{air} with volumetric flow rate of waste effluent (which is equivalent to air).

If $G_{air} < G_{effluent}$, then assumed value of X justified and proceed to next part.

If $G_{air} > G_{effluent}$, then adjust X accordingly and repeat above calculations.

Part 3.

Auxiliary fuel combustion products at 1,200°F, G_p'

$$G_p' = (G_{gas} \text{ scf gas/hr})\,(11.0 \text{ scf prod./scf gas})\,(460 + 1200)/(460 + 60)$$

$$= \underline{\quad 52,670 \quad} \text{ ft}^3\text{/hr}$$

$$= \underline{\quad 14.6 \quad} \text{ ft}^3\text{/sec}$$

Waste effluent volume at 1,200°F, G_E', after removing portion already accounted for in auxiliary fuel burning:

$$G_E' = (1,000 - G_{air})\left(\frac{460 + 1,200}{460 + 60}\right)\frac{1 \text{ min}}{60 \text{ sec}} = \underline{\quad 39.9 \quad} \text{ ft}^3\text{/sec}$$

Total volumetric flow to afterburner:

$$G_{tot}' = G_p' + G_E'$$

$$= \underline{\quad 14.6 \quad} + \underline{\quad 39.9 \quad} = \underline{\quad 54.5 \quad} \text{ ft}^3\text{/sec.}$$

Afterburner Chamber Diameter (Equation C from Problem V.1):

$$D = \left[(4/\pi)\,(G_{tot}')\,/\,(12 \text{ ft/sec})\right]^{\frac{1}{2}} = \underline{\quad 2.40 \quad} \text{ ft.}$$

Afterburner length:

$$L = 2D = (2)\,(\underline{\quad 2.40 \quad}) = \underline{\quad 4.80 \quad} \text{ ft.}$$

Residence time (Equation (E) from Problem V.1):

$$t = L/V_{chamber} = (\underline{\quad 4.80 \quad} \text{ ft})\,/\,(12 \text{ ft/sec}) = \underline{\quad 0.40 \quad} \text{ sec}$$

≥ 0.3; hence O.K.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Coal Burning

COURSE: 427, Combustion Evaluation
LESSON TIME: 105 min.
PREPARED BY: F. A. Iachetta
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 22

Lesson Goal: The goal of this lesson is to provide the student with state-of-the-art information about coal combustion design and practice.

Lesson Objectives: At the end of this lesson the student will be able to:

describe the design characteristics and operating practice of coal-burning equipment, including overfeed, underfeed, and spreader stokers, as well as pulverized and cyclone furnaces;

discuss the parameters that influence the design of overfire and underfire air (in systems which burn coal on grates) and for primary and secondary air (in systems which burn coal in suspension);

describe the influence on the amount of volatile matter and fixed carbon in the coal on its proper firing in a given furnace design; and

describe how changing the ash content and the heating value of coal can influence the combustion as well as the capacity of a specified steam generator.

Student Prerequisite Skills: Course 427, Lessons 6, 9, 15, and 16.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 22.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 9.

2. Steam, Its Generation and Use, 39th Edition, The Babcock and Wilcox Company, 1978.

3. Field Surveillance and Enforcement Guide: Combustion and Incineration Sources, Environmental Protection Agency APTD-1449, June 1973.

4. "Overfire Air Technology for Tangentially Fired Utility Boilers Burning Western U. S. Coal," EPA-600/7-77-117, IERL, Environmental Protection Agency (October 1977).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 22: COAL BURNING
427-22-1	COAL RESERVES - BILLIONS OF TONS
427-22-2	COAL SOURCE DISTRIBUTION
427-22-3	COAL ANALYSIS
427-22-4	INFLUENCE OF FIXED CARBON AND VOLATILE MATTER ON FIRING EQUIPMENT
427-22-5	CHAIN GRATE STOKER
427-22-6	VIBRATING GRATE STOKER
427-22-7	UNDERFEED SINGLE RETORT STOKER
427-22-8	SECTION THRU UNDERFEED STOKER
427-22-9	UNDULATING GRATE STOKER
427-22-10	PULVERIZED COAL BURNER
427-22-11	MULTIFUEL BURNER
427-22-12	SPREADER STOKER SCHEMATIC
427-22-13	SPREADER STOKER
427-22-14	CYCLONE FURNACE
427-22-15	PULVERIZED COAL-FIRED BOILER
427-22-16	CYCLONE FURNACE
427-22-17	BOILER WITH CYCLONE FURNACE
427-22-18	COMBUSTION AIR - THEORETICAL
427-22-19	COMBUSTION AIR - GIVEN ULTIMATE ANALYSIS
427-22-20	EFFECT OF COAL FIRING RATE AND SIZE CONSIST
427-22-21	EFFECT OF EXCESS AIR (FLUE GAS CO_2) ON COMBUSTION EFFICIENCY

I. Introduction
  A. State the lesson objectives
  B. Introduce Coal Rank
    1. Note classification based on ASTM D-388
    2. Point out that moisture is tabulated as natural coal-seam moisture, not the moisture which may be absorbed during handling

Refer to Student Manual, p. 3-19.

  C. Mention the importance of coal resources and sulfur content
    1. Point out reserves are estimates which consider the present technology and economics

Slide 427-22-1

    2. Note coal reserves represent ten times the estimated energy reserves of oil, gas, oil-shale, and nuclear fuel.
  D. Discuss the availability of bituminous coals in terms of sulfur content and source.

Slide 427-22-2

    1. Note that a modern coal-burning generating station requires 3.5 to 5.0 million tons of coal per year per 1,000 MWe, depending on whether Eastern or Western coal is burned.
    2. Point out a 1,000 MWe output requires between 93 and 140 coal car loads per day using modern 100-ton cars.
    3. Illustrate the air-land pollution interaction represented by ash.

II. Coal Properties and Their Influence on Furnace Design
  A. Ultimate and proximate analysis
    1. Remind students that ultimate analysis is a mass basis chemical analysis

Slide 427-22-3

      a. Point out ash contains all noncombustibles and is usually composed of 50% or more of silica
      b. Emphasize use of ultimate analysis to compute air required.
    2. Note the significance of proximate analysis in terms of burning characteristics
      a. Point out residence-time dependency on fixed carbon

Slide 427-22-4

      b. Explain the influence of volatile matter in the design for air distribution because of volatilization
      c. Discuss the fixed carbon/volatile matter influence on stoker overfire and underfire air
      d. Outline the problems of a furnace which burns coal having less heating value and higher moisture content than assumed in the design.
      e. Discuss the influence of moisture and volatile matter on pulverizer operations.
  B. Sulfur content
    1. Note that SO_X emission is directly attributable to presence of sulfur in coal
    2. Account for sulfur in bottom ash, noting about 95% of sulfur usually appears in the stack gases as SO_2
    3. Emphasize influence of sulfur on ash-fusion temperature

    4. Discuss coal's spontaneous ignition behavior and the influence sulfur has on it.
  C. Ash content and fusion temperature
    1. Discuss the effect of ash content on the design of underfire air supply to stoker-grate units
      a. Point out bed-depth air-flow resistance
      b. Note that continuous-discharge grate drives require ash content to stay in a given range
    2. Use emission factor information to illustrate particulate emissions as a function of ash

Refer to Student Manual, p. 5-30.

      a. Note the effect of fly ash re-injection
      b. Point out that the computation is based on the % ash, e.g., 10% ash gives uncontrolled emission from stokers

$$13 \times 10 = 130 \text{ lbs/ton}$$

    3. Fusion temperature
      a. Discuss range needed to avoid "clinkers" or slag.
      b. Note the need to have a temperature high enough to permit particle "freeze" while gas is entrained.
      c. Outline the temperature-viscosity range required for cyclone and wet-bottom furnaces.

III. Coal Firing Arrangements
  A. Explain methods of stoking
    1. Point out that the overfeed principle is essentially the mechanization of a man shovelling coal over a hearth onto a grate-supported fuel bed.
      a. Note the variety of stokers using the overfeed principle
        (i) Chain or travelling grates
        (ii) Vibrating grate

Slide 427-22-5
Slide 427-22-6

      b. Discuss the use of sectionalized wind boxes under the grates.
      c. Point out need to vary underfire air pressure from compartment to compartment
      d. Describe the location of overfire air jets relative to "green" coal.
    2. Discuss the underfeed-stoker operating principle

Slide 427-22-7

      a. Note that the method requires little or no overfire air since volatiles must pass through the burning bed
      b. Illustrate the mechanical design provisions to help deal with a high caking-index problem

Slide 427-22-8
Slide 427-22-9
Slide 427-22-10
Slide 427-22-11

    3. Outline suspension burning principle: the combustion of a highly fluidized solid
      a. Note that high fixed carbon requires either longer residence time or a finer grind of coal.
      b. Explain air distribution noting the use of primary air to transport coal.
      c. Point out there is an option to introduce secondary air either at the burner or elsewhere.

d. Discuss the effects of ash content and wet versus dry bottom on particulate emissions.

4. Describe spreader stoker as a way to combine the suspension and overfeed principles

Refer to Student Manual, pg. 5-30.
Slide 427-22-12
Slide 427-22-13

a. Note the influence of feed coal size consist on dust loading

b. Point out the usual size: 1 to 1½ inches nut and slack, less than 20% fines with an ash content of less than 10%

c. Give boiler steaming-capacity range up to 400,000 lbs/hr

d. Note the use of either dump or continuous ash discharge grates and problems with dump type

5. Discuss the cyclone furnace. Note it is a horizontal, cylindrical, water-cooled furnace.

Slide 427-22-14

a. Note that coal is crushed so that 95% of it passes through a No. 4 screen

b. Explain the conversion of coal to slag and pay particular attention to the importance of ash fusion temperatures

c. Point out lower particulate loading and higher NO_X relative to other coal burning units

B. Burner Location

1. Explain all grate-burning systems

2. Discuss various pulverizer arrangements, including:

a. Front-fired units

b. Front- and back-fired units

c. Corner-fired units

Slide 427-22-15 illustrates a front-fired unit

Slide 427-22-16
Slide 427-22-17

3. Compare cyclone furnace location with other burner systems

4. Discuss load variations which can be tolerated by different burning arrangements

a. Point out single pulverizer turn-down ratio may be 3 or less

b. Note that spreader stokers tend to smoke when operated at 25% of design or less.

C. Define volumetric energy release rate and discuss coal feed rates for each type of feeder

1. Emphasize single underfeed stoker applications usually are limited in size and produce 25,000 to 30,000 lbs/hr steam generation

a. Note the need for ash fusion temperature above 2,400°F and minimal fines in the coal

b. Note the grate criteria of 400,000 Btu/ft^2hr with waterwall or 300,000 Btu/ft^2hr if refractory walls

2. Chain-grate stoker firing rate ranges from 300,000 to 500,000 Btu/ft^2hr

a. Point out that the higher value applies to coal having low ash (5 to 12%) and low moisture (less than 10% moisture) and that the lower value corresponds to 20% moisture, with 3 to 20% ash

3. Discuss the influences of travelling or dump grates on the firing rate for spreader stokers
a. 400,000 Btu/ft^{2}hr maximum for dump grates and up to 750,000 Btu/ft^{2}hr for travelling grates
b. Note the value in either case assumes an ash content of less than 10% and at least medium volatile coal
c. Explain that a response-time advantage can be gained by using a thin fuel bed (2-4 inches)
4. Point out the water-cooled grate feature of vibrating grates
a. Note the maximum release rate of 400,000 Btu/ft^{2}hr
5. Discuss the differing criteria which give rise to a fuel rate based on 450,000 to 800,000 Btu/hr ft^3 in a cyclone furnace.
a. Remind students that a dry-basis ash content between 6 and 25% is desirable
b. Indicate the need for low-sulfur coal
6. Discuss pulverized coal burner energy rates up to 165 x 10^6 Btu/hr
a. Point out the need for high volatility coal
b. Note dependence of fineness on ASTM fixed carbon rank (70 to 80% passing 200 mesh screen with fixed carbon 69 to 86% respectively)

IV. Air Requirements and Distribution
A. Total combustion air
1. Show computation of stoichiometric air using equation 9.1, p. 9-6, Student Manual:

Slide 427-22-18 This slide includes a sample computation with EA.

Slide 427-22-19

$$11.53C + 34.34\left(H_2 - \frac{O_2}{8}\right) + 4.29S$$

a. Note that C, H_2, O_2, S are precent-by-weight of these elements as given in the ultimate analysis.
b. Point out that the analysis used should be converted to an "as fired" condition
c. Explain the $\left(H_2 - \frac{O_2}{8}\right)$ term is "free" hydrogen and point out that this term assumes that all the O_2 in coal is combined with H_2 to form water.
2. Note that the excess air is a percentage of the stoichiometric air

B. Air distribution
1. Explain how air distribution depends on the burning equipment and the coal rank
2. Describe overfire air versus undergrate air for stoker units
a. Note the overfire air is usually provided by a separate forced draft in the range of 20 to 30 inches of water column.

Refer to Student Manual, p. 9-17 and 9-19 for diagram of equipment.

b. Point out that the usual place of introduction coincides with where the "green" coal enters the furnace.
c. Note that overfire air ranges from 5-15% with the larger figure used with higher volatility coals.

3. Describe the cyclone furnace air distribution indicating the three distinct divisions:
    a. Primary air is introduced into the radial burner with coal, 20%.
    b. Secondary air is introduced tangentially at periphery of main barrel with a 300 fps velocity
    c. Up to 5% can be admitted at the center of the radial burner
    d. Note that the total air includes from 10 to 15% excess air.
4. Describe the air flow for pulverized-fired coal nozzles.
    a. Note that primary air, which also transports the coal, is used at a rate of about 2 lb air per lb of coal.
    b. Note that the air velocity ranges from 4,000 to 5,000 fpm with a 3,000 fpm minimum.
    c. Indicate that secondary air may be introduced at the burner and can be as high as 600°F in temperature.
    d. Describe the need to operate the igniters continuously because of reduced furnace temperature, wet coal, or when volatile matter is less than 25%.

V. Instrumentation and Operator Practices
  A. Plant instrumentation
    1. Note that the degree of sophistication depends at least in part on plant size and function.
    2. Point out that the basic instrumentation is designed to assure safe, economic operation.
    3. Describe instrumentation needed to provide measurements of the following factors:
      a. Air flow at various points
      b. Fuel flow
      c. Steam flow, where applicable
      d. Gas flows, where applicable
      e. Flue gas CO_2 or O_2 content
      f. Smoke opacity meter
      g. Forced air, induced air, and furnace draft
      h. Overfire air pressure
  B. Operator practices
    1. Describe the use of flue gas CO_2 or O_2 meters as an operator aid.
      a. Note that the O_2 meter is very useful if the system burns multiple fuels

2. Point out the importance of ash content as a precursor of particulate emission.
3. Show that the size consist of coal supplied to stokers can sharply influence dust loading. — Slide 427-22-20
4. Note the importance of not overloading a unit.
5. Show the efficiency benefit which results from operating with minimum excess air. — Slide 427-22-21
6. Describe the importance of good maintenance in limiting air infiltration.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Solid Waste and Wood Burning

COURSE: 427, Combustion Evaluation
LESSON TIME: 75 min.
PREPARED BY: F. A. Iachetta
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 23

Lesson Goal: The goal of this lesson is to inform the student about the state-of-the-art of solid waste and wood waste combustion and air pollution control.

Lesson Objectives: At the end of this lesson the student will be able to:

list the important similarities and differences in physical and chemical properties of solid waste, wood waste, and coal;

describe the mechanical configurations required for complete combustion of solid waste and wood waste and compare with those for burning coal; and

describe the unique combustion characteristics and emissions from burning unprepared solid waste and refuse-derived fuel.

Student Prerequisite Skills: 427 Course, Lessons 6, 9, 15, 16, and 22.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 23.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 10.

2. Adams, T. N., "Mechanisms of Particle Entrainment and Combustion and How They Affect Emissions from Wood-Waste Fired Boilers," *Proceedings of 1976 National Waste Processing Conference*, ASME, pp. 175-184 (May 1976).

3. Shannon, L. J., Fiscus, D. E., and Gorman, P. G., "St. Louis Refuse Processing Plant," Publication No. EPA-650/2-75-044.

4. Shannon, L. J., Shrag, M. P., Honea, F. I., and Bendersky, D., "St. Louis/Union Electric Refuse Firing Demonstration Air Pollution Test Report," Publication No. EPA-650/2-74-073.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 23: SOLID WASTE AND WOOD BURNING
427-23-1	AVERAGE COMPOSITION OF MUNICIPAL WASTE
427-23-2	AVERAGE ULTIMATE ANALYSIS
427-23-3	WASTE IN AN INCINERATOR STORAGE
427-23-4	HOG FUEL STORAGE PILE
427-23-5	CLARIFIER SLUDGE
427-23-6	ULTIMATE ANALYSIS OF DRY HOGGED FUEL
427-23-7	SIZE AND MOISTURE CONTENT OF HOGGED FUEL COMPONENTS
427-23-8	HEATING VALUES OF BARK AND WOOD
427-23-9	HIGHER HEAT VALUE OF MUNICIPAL WASTE COMPONENTS
427-23-10	FLOW CHART - REFRACTORY WALL INCINERATOR
427-23-11	CHAIN GRATE
427-23-12	RECIPROCATING GRATES
427-23-13	REVERSE RECIPROCATING GRATE
427-23-14	WASTE-FIRED BOILER WITH BARREL GRATE
427-23-15	DIAGRAM OF AIR-SWEPT SPREADER STOKER NOZZLE
427-23-16	AIR-SWEPT SPREADER ON WOOD-FIRED BOILER
427-23-17	ENERGY RELEASE RATES - SOLID WASTE AND WOOD WASTES
427-23-18	HARRISBURG INCINERATOR
427-23-19	SOLID WASTE BOILER WITH RECIPROCATING GRATES
427-23-20	DUTCH OVEN FIRED BOILER
427-23-21	FUEL CELL FIRED WOOD WASTE BOILER
427-23-22	INCLINED GRATE WOOD WASTE BOILER

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Solid Waste and Wood Burning

NOTES

I. Introduction
  - A. State the lesson objectives
  - B. Announce that this lesson is primarily concerned with the combustion of municipal solid waste and wood wastes. Municipal incinerators (50 T/day or larger) and wood fired boilers will be discussed.
    - 1. Discuss the composition of municipal waste to illustrate the variety of components. Slide 427-23-1
      - a. Ultimate analysis of waste including required air computations Slide 427-23-2
      - b. Combustion characteristics of wood and municipal solid wastes are similar because municipal waste contains a high percentage of paper and wood (approximately 45 - 50% as received).
      - c. After metals and glass are removed from municipal waste, the analysis on a moisture-free basis is very similar to wood waste
      - d. Non-flow characteristic of municipal waste usually requires mechanically induced tumbling. Slide 427-23-3
      - e. Hogged fuel exhibits same non-flow characteristic (note sheer face evident in Slide 427-23-4). Slide 427-23-4
      - f. Pulp and paper plants include waste-water clarifier sludge in hogged fuel. Slide 427-23-5
    - 2. Discuss the similarities of the combustibility characteristics of wood hogged fuel and solid waste.
      - a. Proximate analysis (moisture-free) emphasizes the low ash, highly volatile characteristics of wood. Refer to Student Manual, p. 3-23
      - b. Ultimate analysis indicates total carbon content contrasts with low fixed carbon. The implication is that the carbon is largely tied up in volatile matter hydrocarbon. Slide 427-23-6
      - c. Low ash content of wood and hogged fuels means grates must be cooled by air or water when not covered by a deep fuel bed. (Dutch oven designs provide an example using a deep fuel bed.)
      - d. Fuel particle size distribution is important because particles with diameters of 1 mm can be entrained by furnace gases. Wood density is usually 0.1 to 0.5 gm/cc. Slide 427-23-7
      - e. Residence time in wood and waste boilers are in the range of 2 to 4.5 seconds (compared to 1 to 2 seconds in coal-fired units). This residence time is inadequate to assure burnout of larger particles which are entrained (1).
      - f. Wood and wood waste heating values are similar to those of municipal solid waste components. Slide 427-23-8 Slide 427-23-9

II. Municipal Incinerators
  - A. Note that municipal incinerators have been designed primarily to burn wastes as a means of disposal rather than as energy recovery devices. This practice is changing to take advantage of the favorable economics of energy utilization.

B. Discuss why general design considerations do not now result in a reasonably fixed "state of the art."
  1. Present design features of refractory walled incinerators with no energy recovery provisions:

     Slide 427-23-10

     a. Customarily with a primary and secondary combustion chamber.
     b. Sloping front and rear arches to provide radiant energy transfer to the surface of the fuel on the grates.
     c. High excess air (300 to 400%) to hold temperatures within a range tolerable for refractory materials.
  2. Describe batch-fired units which have a time variable furnace temperature which can fluctuate between 1,000 and 2,000°F.
  3. State that modern incinerators are designed to recover energy.
     a. Water-walled furnaces allow firing with 50% excess air.
     b. Continuous feed of combustibles is desirable rather than batch feed.
  4. Describe a variety of firing arrangements, each with a particular means of agitating and tumbling wastes:
     a. Chain-grate units adapted from coal burning technology but not arranged in sections which cause wastes to tumble. Slide 427-23-11
     b. Reciprocating grates which permit alternate rows of grate segments to move. (Note use of air-cooled walls.) Slide 427-23-12
     c. Reverse reciprocating grates are used to tumble waste back up a gentle slope. Allows a width-to-length ratio of 1:2, compared to a 2:1 value for most other systems. Slide 427-23-13
     d. Barrel grates slowly tumble waste to move material through the furnace. Slide 427-23-14
     e. Air-swept nozzles serve as spreader stokers to distribute fuel over a travelling or dump-type grate. Similar nozzles are employed in wood-waste and hogged-fuel-fired boilers. Slide 427-23-15 Slide 427-23-16

III. General Design Parameters for Solid Waste and Wood Waste-Fired Boilers
  A. Consider energy release rates.
     1. Give grate-firing energy rates applicable to mass burners. Slide 427-23-17
        a. 400,000 Btu/hr/ft^2 for batch feeding
        b. 300,000 Btu/hr/ft^2 for continuous (moving) feed grates
     2. Present volumetric energy release rates (about 20,000 Btu/ft^3) and residence time of 2 to 4 seconds depending on feed mechanism.
  B. Describe combustion air design parameters.
     1. Refractory-walled furnaces require 200 to 400% excess air.

    a. Temperatures required are limited by refractory wall material (usually calcium silicate brick).
    b. Cast iron air-cooled wall sections reduce excess air requirements to about 150%.
  2. Note that the high volatile matter of wood or solid waste requires a high percentage of over-fire air.
  3. Describe the use of an arch close to the grate, near the end, to ensure better burn-out; notice that the drying zone requires the greatest under-fire air pressure. Slide 427-23-18
    a. Note: Drying zone with low furnace arch arrangement is evident in the Navy Yard boiler shown in Slide 427-23-19. Low arch at the burn-out end of grate is evident in the Harrisburg incinerator, Slide 427-23-18. Harrisburg also uses the reverse reciprocating grate shown earlier in Slide 427-23-13. Slide 427-23-19
  4. Note that dutch oven furnace designs usually require primary air supplies both under and over fire, with additional secondary air added close to furnace aperture. Slide 427-23-20
  5. Point out that fuel cell concept employed for wood burning is essentially a modification of the primary-secondary zone concept used in solid waste incinerators Slide 427-23-21
  6. Note the use of inclined water-cooled grates to provide several improvements for fuel feed and volatization:
    a. Steepness of input region ensures flow; it assures a relatively thin drying zone on an uncooled refractory section.
    b. Lesser slope near discharge provides for ash accumulation, but also gives somewhat higher temperature bed (thickness of ash insulates) for better burn-out of larger material.
  7. Notice air-swept spreader-stoker units closely resemble coal-fired boilers.

IV. Consider co-firing prepared solid waste with other fuels
  A. Describe the processing necessary to remove metal, glass, and other non-combustibles.
    1. Discuss the shredding operation.
    2. Note the separation of a "light" and heavy fraction.
    3. Describe various methods for storage including prepared pellets or briquettes.
  B. Discuss methods of firing
    1. Describe suspension burning with coal or oil. (Note energy input range of 10 to 20% of total)
    2. Describe use of briquette-form waste fired with coal in underfeed stokers.
    3. Note the problems associated with firing pelletized waste with coal on chain- or travelling-grate stokers.
    4. Discuss co-firing systems where air-swept spreaders fire waste as the main fuel; gas or oil may be used as a secondary fuel.

C. Outline the problems which arise from co-firing waste with coal in units originally designed only for coal.
   1. Note the decreased precipitator efficiency.
   2. Discuss the increase in total stack gas flow; this is a probable cause for reduced ESP performance.
   3. Note the detrimental corrosive effect of high moisture stack gases, caused by high-moisture content of waste.
   4. Note that alterations of stack gas (in response to higher moisture) can be an adverse influence on ESP performance.
   5. Point out that the reduced marketability of fly-ash is caused by large pieces of charred or unburned trash remaining in it.

LESSON PLAN

AIR POLLUTION
TRAINING INSTITUTE

TOPIC: Problem Session VI:
Combustion System
Calculations

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: J. T. Beard
DATE: Nov. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 24

Lesson Goal: The goal of this lesson is to provide the computational methodology used in evaluating selected combustion system problems.

Lesson Objectives: At the end of this lesson the student will be able to:

compute the rate of energy delivered to a boiler, superheater, or economizer;

compute the fuel requirements for a given combustion system;

compute the savings resulting from reduced flue gas losses which occur when a combustion unit is modified to provide a reduction in the amount of excess air.

Student Prerequisite Skills: Course 427, Lessons 6 through 23.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Workbook for Combustion Evaluation in Air Pollution Control, Chapter VI.
2. Chalkboard
3. Hand-held calculator or slide rule

Special Instructions: Assist the students who have difficulty in working Problem VI.1 on their own. Assign Problem VI.2 for homework.

References: Combustion Evaluation in Air Pollution Control

AIR POLLUTION TRAINING INSTITUTE

CONTENT OUTLINE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 427, Combustion Evaluation
Lecture Title: Problem Session VI

Page 2 *of* 2

NOTES

I. Introduction
   A. State the goals and objectives of this lesson
   B. Goals are to be achieved by:
      1. Students working problems independently
         a. In class
         b. Homework assignment
      2. Discussion of solutions of problems

II. Methodology
   A. Assign Problem VI.1: Fuel Requirements for Combustion Installation, to be done by the individual students during the class period.
   B. Assign Problem VI.2: Combustion Improvement, to be started during the class period and to be completed as a homework assignment.
   C. Assist individuals by answering questions regarding solution techniques.
   D. Answers to Problem VI.1 may be confirmed during the class period; and answers to Problem VI.2 are to be confirmed in the Homework Review period.

CHAPTER VI

COMBUSTION SYSTEM CALCULATIONS

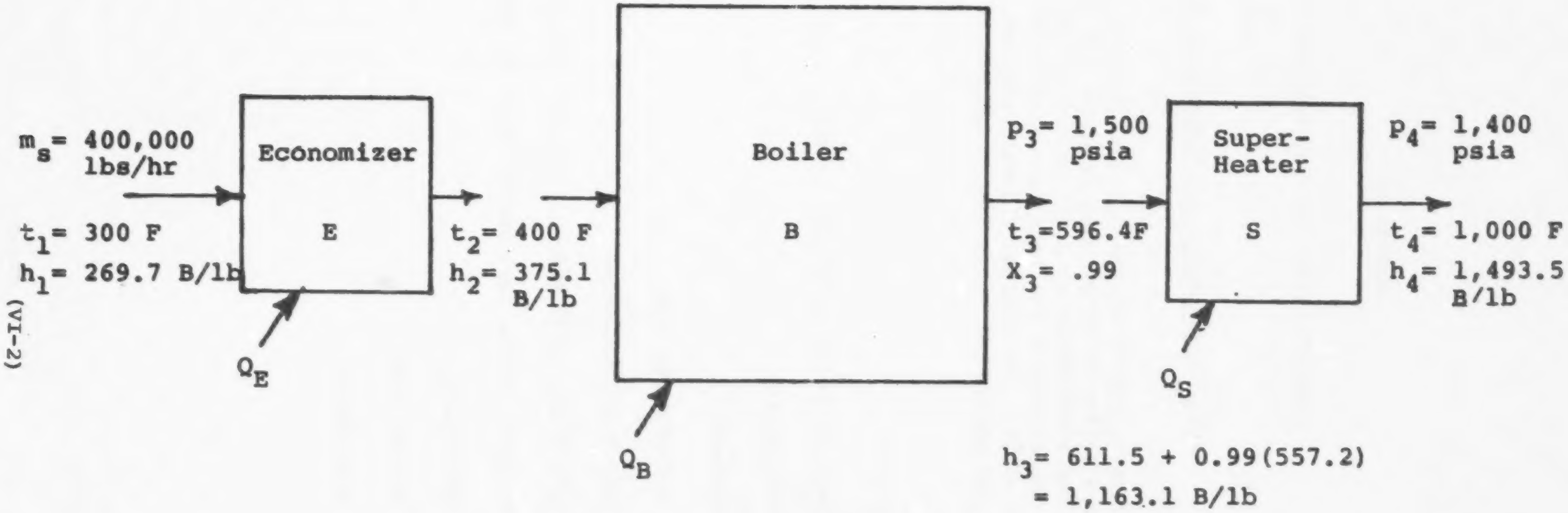
PROBLEM VI.1: Fuel Requirements for Combustion Installation

A steam generator is rated at 400,000 lbs of steam per hour. Steam (99% dry) leaves the boiler at 1,500 psia pressure and enters a superheater. Steam leaves the superheater at 1,400 psia pressure and a temperature of 1,000°F. The feedwater for this unit enters the economizer at 300°F and leaves at 400°F. The overall thermal efficiency of the steam generator is 74%. The energy and water losses associated with blowdown may be neglected.

Compute:

1. The rate of energy delivered to the:
   (a) economizer,
   (b) boiler,
   (c) superheater, and
   (d) the total delivered
2. The fuel energy required, million Btu/hr
3. The fraction of the fuel energy which is absorbed in the
   (a) economizer,
   (b) boiler, and
   (d) superheater.

SCHEMATIC DIAGRAM FOR PROBLEM VI.1


m_s = 400,000 lbs/hr
t_1 = 300 F
h_1 = 269.7 B/lb
Economizer
E
Q_E
t_2 = 400 F
h_2 = 375.1 B/lb
Boiler
B
Q_B
p_3 = 1,500 psia
t_3=596.4F
X_3 = .99
Super-Heater
S
Q_S
p_4 = 1,400 psia
t_4 = 1,000 F
h_4 = 1,493.5 B/lb
h_3 = 611.5 + 0.99(557.2)
= 1,163.1 B/lb

Solution to Problem VI.1:

From the steam tables one may determine the enthalpy values of the feedwater and steam:

Economizer inlet: $t_1 = 300^{\circ}F$, $h_1 = 269.7$ Btu/lb

Economizer exit: $t_2 = 400^{\circ}F$, $h_2 = 375.1$ Btu/lb

Boiler exit: $p_3 = 1{,}500$ psia $h_3 = 611.5 + X\ (557.2)$

$t_3 = 596.39^{\circ}F$ $= 611.5 + .99\ (557.2)$

$X = .99$ $= 1163.1$ Btu/lb

Superheater exit: $p_4 = 1{,}400$ psia $h_4 = 1493.5$ Btu/lb

$t_4 = 1{,}000^{\circ}F$

1. Compute the energy delivered to each section using Equation 4.13 on p. 4-10 of the Student Manual.

   a. Economizer:

$$Q_{s_E} = m_s\ (h_2 - h_1)$$

$$= 400{,}000\ \frac{\text{lb steam}}{\text{hr}}\ (\ 375.1\ -\ 269.7\ )\ \frac{\text{Btu}}{\text{lb}}$$

$$= \underline{\ 42 \times 10^6\ }\ \text{Btu/hr}$$

   b. Boiler:

$$Q_{s_B} = m_s\ (h_3 - h_2)$$

$$= 400{,}000\ \frac{\text{lb steam}}{\text{hr}}\ (1{,}163.1 - 375.1\ )\ \frac{\text{Btu}}{\text{lb}}$$

$$= \underline{\ 315 \times 10^6\ }\ \text{Btu/hr}$$

   c. Superheater:

$$Q_{s_S} = m_s\ (h_4 - h_3)$$

$$= 400{,}000\ \frac{\text{lb steam}}{\text{hr}}\ (1{,}493.5 - 1{,}163.1\ )\ \frac{\text{Btu}}{\text{hr}}$$

$$= \underline{\ 132 \times 10^6\ }\ \text{Btu/hr}$$

d. Total:

$$Q_{s_T} = Q_{s_E} + Q_{s_B} + Q_{s_S}$$

$$= (42 \times 10^6) + (315 \times 10^6) + (132 \times 10^6) \text{ Btu/hr}$$

$$= \underline{489 \times 10^6} \text{ Btu/hr}$$

2. The fuel energy input required may be determined using Equation 4.9 on p. 1-8 of the Student Manual.

$$Q_H = \frac{Q_s}{\eta} = \frac{(489 \times 10^6) \text{ Btu/hr}}{(\ .74\ )}$$

$$= \underline{661 \times 10^6} \text{ Btu/hr}$$

3. The fraction of the fuel energy which is absorbed:

a. Economizer:

$$\frac{Q_{s_E}}{Q_H} = \frac{(42 \times 10^6)}{(661 \times 10^6)} = \underline{.063} = \underline{6.3}\ \%$$

b. Boiler:

$$\frac{Q_{s_B}}{Q_H} = \frac{(315 \times 10^6)}{(661 \times 10^6)} = \underline{.477} = \underline{47.7}\ \%$$

c. Superheater:

$$\frac{Q_{s_S}}{Q_H} = \frac{(132 \times 10^6)}{(661 \times 10^6)} = \underline{.20} = \underline{20.0}\ \%$$

PROBLEM VI.2: **Combustion Improvement**

Combustion modification of a boiler resulted in changing the excess air as may be determined from the following Orsat analyses of the flue gas:

Gas	Before Modification	After Modification
CO_2	10.1%	15.0%
O_2	8.3	3.1
CO	0.1	0.0

The fuel fired was lignite coal which has the following analysis: 0.22% S, 6.39% H_2, 37.37% C, 0.61% N_2, and 44.99% O_2. The heating value is 6,010 Btu/lb and the proximate analysis is: 36.93% moisture, 24.92% volatile matter, 27.72% fixed carbon, and 10.43% ash.

The unit operates 7,700 hr per year with an average load of 5.3 tons of coal per hour with a fuel cost of 75¢ per 10^6 Btu. Assume that before and after the modification, flue gas temperature was 355°F; the refuse was 0.1062 lb per lb of coal; and the average combustion air was at 75°F.

Compute:

1. The excess air
   - (a) before the modification,
   - (b) after the modification.
2. The theoretical air required to burn a pound of the specified coal.
3. The theoretical flue gas produced from firing a pound of coal.
4. The actual flue gas produced per pound of coal
   - (a) before the modification,
   - (b) after the modification.
5. The change in flue gas energy loss per pound of coal.
6. The value of the annual savings from reduced flue gas losses, which occur because of the modification

Solution to Problem VI.2:

1. Compute excess air knowing that:

$$N_2 = 100\% - CO_2\% - O_2\% - CO\%$$

a. Before modification:

$$N_2 = 100\% - (10.1) - (8.3) - (0.1) = \underline{81.5}\ \%$$

Determine %EA from Equation (1), p. 5-23 of the Student Manual:

$$EA = \frac{(O_{2p}) - 0.5\,(CO_p)}{0.264\ N_2 - (O_{2p} - 0.5\ CO_p)} \times 100\%$$

$$= \frac{(8.3) - 0.5\,(0.1)}{0.264\,(81.5) - (8.3 - 0.5\,(0.1))} \times 100\%$$

$$= \underline{62.2}\ \%$$

b. After modification:

$$N_2 = 100\% - (15.0) - (3.1) - (0.0)$$

$$= \underline{81.9}\ \%$$

$$EA = \frac{(3.1) - 0.5\,(0)}{0.264\,(81.9) - (3.1 - 0.5\,(0))} \times 100\%$$

$$= \underline{16.7}\ \%$$

2. The theoretical air required is found from Equation 4.1 on p. 4-4 of the Student Manual

$$A_t = 11.53\ C + 34.34\ (H_2 - \frac{O_2}{8}) + 4.29\ S$$

$$= 11.53\,(.3737) + 34.34\,(.0639 - \frac{(.4499)}{8}) + 4.29\,(.0022)$$

$$= \underline{4.58}\ \text{lb air/lb coal}$$

(VI-6)

3. The theoretical flue gas per pound of coal fired may be obtained from Equation 4.2 on p. 4-5 of the Student Manual, with $m_f = 1$:

$$G = (m_f - \text{noncombustible}) + m_f A_t$$

$$= 1 - (.1043) + 1 \ (4.58)$$

$$= \underline{\quad 5.48 \quad} \text{ lb gas/ lb coal}$$

4a. Before the modification the actual flue gas per pound of coal was

$$G_f = A_E + G$$

$$= EA \ (A_t) + G$$

$$= (.622) \times (4.58) + (5.48)$$

$$= \underline{\quad 8.33 \quad} \text{ lb gas/ lb coal fired}$$

4b. After the modification the actual flue gas was:

$$G_f = (.167) \times (4.58) + (5.48)$$

$$= \underline{\quad 6.24 \quad} \text{ lb gas/ lb coal fired}$$

5. As it was stated that the average ambient and flue gas temperatures did not change after the modification, the difference in flue gas energy loss may be determined using Equation 4.12 on p. 4-8 of the Student Manual

$$\Delta Q_{fg} = (G_{f\ \text{before}} - G_{f\ \text{after}}) \ C_p \ (t_{fg} - t_{amb})$$

$$= (8.33 - 6.24) \times (0.25 \ \frac{\text{Btu}}{\text{lb}^\circ\text{F}}) \times (355 - 75)$$

$$= \underline{\quad 146 \quad} \text{ Btu/lb coal fired}$$

6. The value of the annual savings resulting from reduced flue gas losses will be:

$$\text{Annual savings} = \frac{\text{cost}}{\text{Btu}} \times \Delta Q_{fg} \ \frac{\text{Btu}}{\text{lb coal}} \times m_f \ \frac{\text{lb coal}}{\text{hr}} \times \text{time} \ \frac{\text{hr}}{\text{year}}$$

$$= \frac{\$.75}{10^6 \text{ Btu}} \times (\ 146\ ) \frac{\text{Btu}}{\text{lb coal}} \times (\ 5.3 \times 2000) \frac{\text{lb coal}}{\text{hr}}$$

$$\times \ (\ 7{,}700) \ \frac{\text{hr}}{\text{year}}$$

$$= \underline{\ \$\ 8940\ } \text{ per year}$$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Controlled-Air Incinerators

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: J. T. Beard
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 25

Lesson Goal: The goal of this lesson is to provide the student with information about controlled-air incineration equipment and the influence of operating parameters on air pollution emissions.

Lesson Objectives: At the end of this lesson the student will be able to:

describe the combustion principles and pollution emission characteristics of controlled-air incinerators contrasted with those of single and multiple-chamber designs;

identify operating features which may cause smoke emissions from controlled-air incinerators; and

relate the temperature of gases leaving the afterburner to the amount of auxiliary fuel needed by the afterburner.

Student Prerequisite Skills: Course 427, Lesson Number 23

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 25

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 11.

2. Hoffman, Ross, "Evaluation of Small Modular Incinerators in Municipal Plants, " Final Report of Contract No. 68-01-3171, Office of Solid Waste Management, USEPA (1976).

3. "Interim Guide of Good Practice for Incineration at Federal Facilities," AP-46, National Air Pollution Control Administration, Public Health Service, Raleigh, N.C. (November 1969).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 25: CONTROLLED AIR INCINERATOR
427-25-1	AVERAGE EMISSION FACTORS FOR REFUSE COMBUSTION
427-25-2	FLUE FED SINGLE CHAMBER INCINERATOR
427-25-3	APARTMENT HOUSE INCINERATOR WITH SEPARATE STORAGE BIN
427-25-4	MULTIPLE-CHAMBER RETORT INCINERATOR
427-25-5	MULTIPLE-CHAMBER IN-LINE INCINERATOR
427-25-6	MULTIPLE-CHAMBER IN-LINE INCINERATOR
427-25-7	CONTROLLED AIR INCINERATOR
427-25-8	CONTROLLED PROPORTIONATE AIR DISTRIBUTION
427-25-9	AIR DELIVERY BLOWER
427-25-10	PRIMARY CHAMBER PRODUCES VOLATILE GASES
427-25-11	SECONDARY CHAMBER
427-25-12	TEMPERATURE CONTROLLER
427-25-13	RELATIVE SIZE OF PRIMARY AND SECONDARY CHAMBERS
427-25-14	FACTORY MANUFACTURED
427-25-15	MODULAR UNIT AT MUNICIPAL FACILITY
427-25-16	CHARGING OF AUTOMATIC FEED HOPPER
427-25-17	ASH REMOVAL DOORS
427-25-18	AUXILIARY FUEL BURNER
427-25-19	MULTIPLE AUXILIARY BURNERS FOR PRIMARY CHAMBER OF PATHOLOGICAL WASTE INCINERATOR
427-25-20	COMPACT WASTE CHARGE
427-25-21	CHARGING WITH OPEN DOOR
427-25-22	MODIFY CONTROLLER TEMPERATURE SETTING
427-25-23	DAMAGED REFRACTORY AND UNDERFIRE AIR PIPE
427-25-24	UNDERFIRE AIR SUPPLY ORIFICES

SLIDE NUMBER	TITLE OF SLIDE
427-25-25	INCINERATOR WITH STEAM GENERATION
427-25-26	INCINERATOR WITH CONTINUOUS FEED AND ASH REMOVAL

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Controlled-Air Incinerators

Page 5 *of* 7

	NOTES
I. Introduction	
A. State the lesson objectives	
B. Describe briefly single-chamber incinerator design features and emissions	Slide 427-25-1
1. Smoke, CO, HC, particulates	
2. Single-chamber incinerators, banned 1957 in Los Angeles	Slide 427-25-2
3. Flue-fed incinerator design modifications required because of	
a. Poor ability to control residence time (gas velocities varied with burning rate and natural draft)	
b. Poor turbulence	
c. Low combustion temperatures due to high excess air	
d. Flue-fed features causing poor control of burning	
e. Overloading incinerators by unskilled personnel	
C. Describe design improvements and emissions of multiple-chamber incinerators	
1. Give examples of the emissions of multiple-chamber incinerators	Slide 427-25-3
2. Design features	
a. Gas speed and directional changes to aid turbulence (consider both in-line and retort designs)	
b. Secondary air and auxiliary fuel burners to improve combustion in the second chamber (however, many units had secondary air temperature from only 650 to 900°F	Slide 427-25-4
c. Larger sizes and damper controls to provide longer residence time (however air control was still too erratic)	Slide 427-25-5
D. Summarize Los Angeles design standards of 1960	Slide 427-25-6
1. Control on geometry, loading rate, auxiliary fuel	
2. Calculation procedure	
a. Required temperature	
b. Maximum velocities	
E. Provide background information about federal incinerator performance standards (1969)	
1. Contrast performance standards with design standards	
2. State the allowable emissions	
3. Describe scrubber requirements	
F. Discuss the greater control of incinerators required with some State Implementation Plans	
II. Controlled air incinerator characteristics	Slide 427-25-7
A. Discuss distinguishing features and give example values	Slide 427-25-8
1. Forced draft	Slide 427-25-9
2. Less than stoichiometric air in primary chamber	
3. Volatilization with partial oxidation in primary chamber	Slide 427-25-10

      - a. Auxiliary burners assure minimum temperature
      - b. Low primary air rates, water sprays, continuous charging limit maximum temperature
      - c. Air distributed below the charge on the hearth rather than through the grate
      - d. Fuel-bed agitation only during charging, rather than continuous as with modern municipal incinerators
    - 4. Oxidation completed in secondary chamber, afterburner
      - a. Secondary air — Slide 427-25-11
      - b. Temperature controlled by auxiliary burner — Slide 427-25-12
      - c. Residence time
  - B. Give examples of various designs — Slide 427-25-13
    - 1. Geometry and relative size
    - 2. Starved air or controlled-air vs. multiple chamber features
  - C. Explain why particulate loading is lower than for multiple-chamber units
    - 1. Lower velocities in primary chamber (less entrainment)
    - 2. Better control of combustion
      - a. More uniform volatilization rate
      - b. More uniform velocities
      - c. Control of residence time
      - d. Higher combustion temperatures
- III. Other design features — Slide 427-25-14
  - A. Cite examples of advantages for factory production
    - 1. Design standardized for given model number
    - 2. Modular features
      - a. Size below that of new source performance standards (400 to 3,000 lb/hr) — Slide 427-25-15
      - b. Multiple units for larger load requirements
    - c. Reliability of performance
  - B. Describe batch operation cycle and give example times
    - 1. Full burning rate operation, 7 to 9 hrs.
      - a. Intermittent charging, 8 to 10 min. — Slide 427-25-16
    - 2. Burn down requiring afterburners, 3 hrs.
    - 3. Overnight cooling
    - 4. Ash removal — Slide 427-25-17
      - a. Give examples of typical waste weight and volume reduction
    - 5. Preheating of refractory
    - 6. Operation at full burning rate
  - C. Describe auxiliary fuel consumption — Slide 427-25-18
    - 1. Increases with moisture content of refuse
    - 2. Pathological waste burning requirements — Slide 427-25-19
      - a. Multiple auxiliary burners in primary zone
      - b. Continuous afterburner operation
- IV. Particulate or smoke control
  - A. Give examples of emission performance
    - 1. 0.03 to 0.08 grains/scf at 12% CO_2
    - 2. Varies with operation and design

- B. State the causes of high emissions
  - 1. Overloading unit (high air velocity in primary chamber),
  - 2. Reducing auxiliary fuel at afterburner (to cut fuel costs)
  - 3. Batch charging through open door which disturbs air velocity control — Slide 427-25-20
  - 4. Batch charging disturbs fuel bed
  - 5. Charge consisting of compressed or packaged materials, rather than loose materials
  - 6. Variable moisture in charge
- C. Describe the methods for reducing emissions
  - 1. Modify charging technique — Slide 427-25-21
  - 2. Install ram charging device and double-door interlock features to avoid extra air inflow during charging — Slide 427-25-22
  - 3. Do not overcharge
  - 4. Modify automatic controller temperature setting for additional auxiliary fuel
  - 5. Proper maintenance of burners, refractory walls, and underfire air supply — Slide 427-25-23
  - 6. May be abused if operated as excess air incinerator with extra primary air blowers provided to increase energy release: — Slide 427-25-24
    - a. Will cut afterburner fuel costs,but
    - b. Will increase smoke and particulates, and
    - c. Will increase maintenance costs somewhat

V. Other important features

- A. Describe possible system economic advantages by providing a waste heat boiler — Slide 427-25-25
  - 1. Will substantially improve economics if
    - a. Waste stream is guaranteed
    - b. Purchaser available for total steam produced
- B. Large units may provide continuous feed and continuous ash removal features
  - 1. Reduces thermal shock to refractory — Slide 427-25-26
  - 2. Increases daily loading by providing 24-hour burn period rather than 8- to 10-hour charge period
  - 3. May require scrubber or other flue gas control to meet new source performance standards for municipal incinerators (.08 grains/scf at 12% CO_2)

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Combustion of Hazardous Wastes

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: L. U. Lilleleht
DATE: Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 26

Lesson Goals: To provide the student with an understanding of the special requirements for the destruction of hazardous waste by combustion.

Lesson Objectives: At the end of this lesson, the student will be able to:

cite special requirements associated with the combustion of hazardous liquid and solid wastes;

recite the special requirements for treating the combustion products to control pollutant emissions from incineration operations;

list examples of substances and/or elements which cannot be controlled by incineration;

describe the fuel requirements necessary to dispose hazardous waste materials; and

list a number of hazardous waste materials (including polychlorinated biphenyls — PCB's — pesticides, and some other halogenated organics) which may be disposed of successfully through proper liquid incineration devices; give the required temperatures and residence time to achieve adequate destruction

Student Prerequisite Skills: Course 427, Lessons 5, 17, 20, 23, 24.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector

2. Slide set for Lesson 26.

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapters 10, 11, 13, 15.

2. Scurlock, A. C., et al., "Incineration in Hazardous Waste Management," SW-141, USEPA (1975).

3. "Summation of Conditions and Investigations for the Complete Combustion of Organic Pesticides," Report No. EPA-600/2-75-044 (October 1975).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 26: COMBUSTION OF HAZARDOUS WASTE
427-26-1	COMPARISON OF THERMAL DESTRUCTION OF PESTICIDES AND PCB's
427-26-2	THERMAL DESTRUCTION ZONES FOR VARIOUS PESTICIDES
427-26-3	SUBMERGED-COMBUSTION INCINERATOR
427-26-4	KEPONE INCINERATION TEST SYSTEM
427-26-5	ROTARY KILN INCINERATOR
427-26-6	FLUIDIZED-BED INCINERATOR SCHEMATIC

AIR POLLUTION TRAINING INSTITUTE

CONTENT OUTLINE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 427, Combustion Evaluation
Lecture Title: Combustion of Hazardous Waste

NOTES

- I. Introduction
  - A. State the goals and objectives of this lesson.
  - B. Show the need for disposal of hazardous wastes.
  - C. Examine the advantages of disposal by incineration:
    - 1. Combustion technology developed
    - 2. Applicability to most organics
    - 3. Heating value may be recoverable
    - 4. Ability to handle large volumes
    - 5. Large land area not required
  - D. Consider possible disadvantages
    - 1. Costly and complicated equipment
    - 2. Auxiliary energy often needed
    - 3. Combustion products may be polluting
    - 4. Solid residues may be toxic
- II. General Incineration Criteria
  - A. Stress similarities to other incineration methods, but that it must be more stringently controlled
    - 1. There are no generally applicable rules at present
    - 2. Limited knowledge of design details
  - B. Point out that for toxic materials:
    - 1. Higher destruction efficiency required
      - a. 99.99% typically for pesticides
    - 2. Much higher temperature and residence times required
      - a. Destruction starts at similar temperatures as that for hydrocarbons
      - b. High degree of combustion completion requires stringent operating conditions
  - C. Show the need to scrub (or treat) combustion product gases.
  - D. Explain that organic products with dangerous heavy metals should not be incinerated.
- III. Equipment types being used
  - A. Present examples of equipment
    - 1. Rotary kilns
    - 2. Multiple-hearth incinerators
    - 3. Liquid-injection incinerators
    - 4. Fluidized beds
    - 5. Molten-salt devices
    - 6. Wet oxidation
    - 7. Multiple-chamber incinerators
    - 8. Gas combustors
    - 9. Pyrolysis units
- IV. Halogenated and Sulfonated Materials
  - A. Note that these materials should not be flared
  - B. Discuss hydrogen chloride (and other halide) emissions
    - 1. When H to Cl ratio is greater than 5 to 1
    - 2. Scrub with caustic
  - C. Consider the products of chlorinated hydrocarbon
    - 1. With H to Cl ratio less than 5 to 1
    - 2. Hard to remove
    - 3. Add natural gas or steam to produce HCl instead
  - D. Examine plastic waste-handling practices

Slide 427-26-2 or refer to Student Manual, p. 15-12.

Slide 427-26-1 or refer to Student Manual, p. 15-12.

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Combustion of Hazardous Wastes

Page 5 **of** 5

NOTES

- E. Evaluate control of pollutant emissions in the effluent gas
  - 1. Scrubbing of effluent
  - 2. Submerged combustion incinerator

Slide 427-26-3 or refer to Student Manual, p. 15-11.

- V. Pesticides and Toxic Wastes
  - A. Discuss detoxification by incineration
    - 1. If toxicity is due to molecular structure rather than elemental composition
    - 2. More stringent temperature and residence-time requirements

Slide 427-26-2

  - B. Be on the lookout for toxic product gases
    - 1. Cyanide from organonitrogen pesticides
    - 2. Others
  - C. Consider more complex equipment
    - 1. Careful siting considerations because there will inevitably be emissions of small quantities of pesticides or toxic products

Slide 427-26-4 or refer to Student Manual, p. 15-13.

- VI. Polychlorinated Biphenyls (PCB's)
  - A. Remind students PCB's are extremely stable and persistent
  - B. Note PCB incineration requires more drastic conditions than most pesticides
- VII. Propellants, Explosives, and Pyrotechnics (PEP)
  - A. State that incineration is the most acceptable disposal method
  - B. Recommend dilution with inerts before feeding them to the incinerator
  - C. Evaluate equipment used:
    - 1. Rotary kilns and furnaces
    - 2. Fluidized beds

Slide 427-26-5 or refer to Student Manual, p. 15-14.

  - D. Emphasize the need to control emissions
    - 1. Very little is known about the type and quantities of emissions
    - 2. Little has been done to control emissions in the past

Slide 427-26-6 or refer to Student Manual, p. 15-14.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: NO_X Control Theory

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: J. T. Beard
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 27

Lesson Goal: The goal of this lesson is to provide the student with information about the various mechanisms of formation and control of NO_X and to provide examples of the amounts of NO_X control available.

Lesson Objectives: At the end of this lesson the student will be able to:

identify three of the major stationary sources of NO_X emissions;

locate and use emission factors to estimate the amount of NO_X emitted from a potential combustion source;

describe the difference between mechanisms for forming "Thermal NO_X" and "Fuel NO_X";

describe the various techniques for NO_X control: flue-gas recirculation, two-stage combustion, excess air control, catalytic dissociation, wet-scrubbing, water injection, and reduced fuel burning rate; and

recall the amount of NO_X control available from particular combustion modification examples.

Student Prerequisite Skills: Course 427, Lessons 5, 6, 17, 18, and 22

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 27

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 16.

2. Strauss, Werner, Air Pollution Control, Part I, Wiley Interscience, New York (1971).

3. Wark, K., and Werner, C. F., Air Pollution, Its Origin and Control, Harper and Row, Publishers, New York (1976).

4. "Control Techniques for Nitrogen Oxide Emissions from Stationary Sources," Second Edition, EPA-450/1-78-001, U. S. Environmental Protection Agency (Jan. 1978).

5. "Reference Guideline for Industrial Boiler Manufacturers to Control Pollution with Combustion MOdification," EPA-600/8-77-003b, Industrial Environmental Research Laboratory, U. S. Environmental Protection Agency (Jan. 1977).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 27: NO_X CONTROL THEORY
427-27-1	SUMMARY OF 1974 STATIONARY SOURCE NO_X EMISSIONS
427-27-2	ANNUAL NATIONWIDE NO_X EMISSION PROJECTIONS TO 2000
427-27-3	EXAMPLE OF TRANSIENT SMOG CONDITIONS IN LOS ANGELES, CA
427-27-4	EXAMPLE OF EXPERIMENTAL SMOG CHAMBER DATA
427-27-5	GENERALIZED PHOTOCHEMICAL REACTIONS
427-27-6	GENERALIZED PHOTOCHEMICAL REACTIONS (CONTINUED)
427-27-7	THERMAL NO_X FORMATION: CLASSICAL CHEMICAL MODEL
427-27-8	THERMAL NO_X FORMATION: SIMPLIFIED MODEL
427-27-9	THEORETICAL CURVES FOR NO CONCENTRATION VS. TEMPERATURE
427-27-10	EFFECT OF LOW EXCESS AIR, OIL FUEL
427-27-11	TWO-STAGE COMBUSTION
427-27-12	TWO-STAGE COMBUSTION, OIL FUEL
427-27-13	EFFECT OF BURNER STOICHIOMETRY ON NO_X, COAL COMBUSTION
427-27-14	NO_X REDUCTION BY FLUE GAS RECIRCULATION
427-27-15	EFFECT OF FGR ON NO EMISSIONS
427-27-16	EFFECTS OF NO_X CONTROL METHODS
427-27-17	RANGE OF UNCONTROLLED UTILITY BOILER NO_X EMISSIONS
427-27-18	EFFECT OF FIRING METHOD, OIL FUEL
427-27-19	NO_X EMISSIONS WITH WATER INJECTION FOR NATURAL GAS-FIRED GAS TURBINE
427-27-20	EFFECT OF TEMPERATURE ON NO REDUCTION WITH AMMONIA INJECTION

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: NO_x Control Theory

NOTES

- I. Introduction to NO_x
  - A. State the lesson objectives
  - B. Present the sources of NO_x
    - 1. Natural (volcanoes, forest fires)
    - 2. Vehicular
    - 3. Stationary
      - a. Utility boilers for electric power generation (42%)

        Slide 427-27-1
      - b. Internal combustion engines, diesel and spark ignition engines, gas turbines, for petroleum, electric power, agricultural, and general industrial applications (22%)
      - c. Industrial boilers for heating and electrical generation (18%)
      - d. Commercial and residential space heating (9%)
  - C. Describe NO_x emission factors

    See Student Manual, Chapter 16, Attachment 16-6
    - 1. Average values dependent upon
      - a. Fuel
      - b. Equipment design
  - D. Discuss concerns about NO_x emissions
    - 1. Potential growth

      Slide 427-27-2
    - 2. Regulations
      - a. New Source Performance Standards
      - b. State and local standards
    - 3. Relationship in smog formation

      Slide 427-27-3
- II. Introduction to the Formation of NO

  Slide 427-27-4
  - A. Explain the formation of nitrogen oxides

    Slide 427-27-5
    - 1. Primarily formed as NO

      Slide 427-27-6
      - a. Define "Thermal NO_x"
      - b. Define "Fuel NO_x"
    - 2. Oxidation of NO to NO_2 in air
    - 3. Other oxides of nitrogen (N_2O, nitrous oxide; N_2O_3, nitrogen trioxide; and N_2O_5, nitrogen pentoxide)
  - B. Explain "Thermal NO_x" formation

    Slide 427-27-7
    - 1. Classical chemical model for NO formation
      - a. High temperature dissociation of O_2

        $$O_2 \rightleftharpoons 2O$$
      - b. Nitrogen reactions

        $$O + N_2 \rightleftharpoons NO + N$$

        $$N + O_2 \rightleftharpoons NO + O$$
      - c. Simplified model

        Slide 427-27-8

        $$N_2 + O_2 \underset{K_R}{\overset{K_F}{\rightleftharpoons}} 2NO$$

- 2. Model for rate of production of NO

  $$\frac{d(NO)}{dt} = K_F (N_2) (O_2) - K_R (NO)^2$$

    - a. Define symbols
    - b. Present temperature influences
    - c. Describe transient features of combustion
    - d. Describe and give example of equilibrium NO concentrations — Slide 427-27-9
    - e. Explain how real combustion varies from equilibrium
    - f. Explain the concepts of dissociation and cool down "freezing" of NO
- C. Explain "Fuel NO_x" formation
  - 1. Describe and give examples of chemically combined nitrogen in fuel
    - a. Coal (e.g., 0.5 to 2.0%)
    - b. Fuel oil (e.g., 0.1 to 0.5% for No. 6 and around 0.01% for No. 2)
    - c. Natural gas contains nitrogen in uncombined form
  - 2. Present factors influencing "Fuel NO_x"
    - a. 10 to 60% fuel nitrogen becomes NO
    - b. Depends on oxygen available
    - c. Fuel-rich combustion, nitrogen becomes N_2
    - d. Lean combustion, fuel nitrogen becomes NO
    - e. More NO with high-fuel volatility
    - f. More NO with intensive fuel/air mixing

III. NO_x Control Theory

- A. Present examples of control by fuel change
  - 1. Change from high nitrogen No. 6 fuel oil to No. 2
  - 2. Specify low-nitrogen-content No. 6 fuel oil
    - a. Nitrogen content influenced by refining processes, blending, and crude stock.
  - 3. Change from coal to oil or from oil to gas
    - a. Limited by furnace adaptability, fuel availability, and costs.
    - b. More coal rather than less as boiler fuel expected in the future
- B. Introduce excess air reduction for NO_x control
  - 1. Effective for "Thermal NO_x"
    - a. Less oxygen available limits oxidation of molecular nitrogen
  - 2. Effective for "Fuel NO_x"
    - a. Less oxygen available causes tendency for fuel nitrogen to form N_2
  - 3. Oil-fired unit example — Slide 427-27-10
    - a. Now larger units operate with 2 to 5% excess air (.4 to 1% excess O_2)
    - b. Previous values were 10 to 20% excess air (2 to 4% excess O_2).
    - c. Reduced excess air limits conversion of SO_2 to SO_3 (and the related dew point/corrosion problems)

        d. Low excess air operation, more difficult than in coal combustion
C. Give example of two-stage combustion for NO_X control — Slide 427-27-11
    1. Initial combustion, fuel-rich — Slide 427-27-12
    2. Energy extraction by heat exchange surfaces
    3. Secondary air provides for full oxidation with overall excess air
    4. May be accomplished by — Slide 427-27-13
        a. Overfire air ports
        b. Burner-out-of-service
        c. Burner redesign to reduce swirl (turbulence/hot spots)
D. Give examples of reduced combustion temperature for NO_X control
    1. Limits the value of K_F, foward reaction coefficient (which essentially doubles for every 70°F increase after 3,000°F)
    2. Flue-gas recirculation — Slide 427-27-14
        a. Rate of reaction reduced by introducing inert flue gases (CO_2, N_2, H_2O) into combustion zone — Slide 427-27-15
        b. Reduced fuel rate implies reduced load — Slide 427-27-16
        c. Inert gases act as heat sink, lower temperature
        d. Thermal efficiency reduced unless adequate heat exchange available
E. Give examples of influence of equipment design on NO_X emissions — Slide 427-27-17, Slide 427-27-18
    1. Design influences
        a. Fuel/air mixing
        b. Proximity of flames to heat exchange surface
        c. Operation of burner influenced by adjacent burners
    2. Give examples
        a. Cyclone furnaces, largest uncontrolled NO_X emissions
        b. Front wall (horizontal) and opposed wall furnaces, somewhat less than from cyclone
        c. Tangential-fired furnaces considerably less emissions
F. Give example of influence of soot blowing frequency on NO_X emissions
    1. Cleaner heat exchange surfaces
        a. Higher heat transfer rate (less insulation by deposits)
        b. Lower combustion temperatures (due to more rapid energy extraction)
G. Describe water injection into gas turbine for NO_X control — Slide 427-27-19
    1. Acts as heat sink
    2. Reduces "Thermal NO_X"
    3. Effective with water-to-fuel-mass ratios up to 1.2
H. Describe flue gas treatment for NO_X control

1. Dry flue-gas method widely used in Japan
    a. Effective for oil and gas combustion
    b. Ammonia injection creates reducing atmosphere
    c. Flue-gas temperatures 100 to 700°F
    d. Catalyst required
    e. Research is underway to apply this technique to particulate and SO_2 laden gas streams
2. Dry method for higher temperature gases

Slide 427-27-20

    a. Ammonia injected as combustion gases reach convection zone of utility boiler
    b. Gas temperatures around 1,300°F
    c. Up to 60% NO_X reduction demonstrated
3. Wet flue-gas treatment used in Japan
    a. Strong oxidant required (ozone or chlorine dioxide)
    b. Converts NO to NO_2 or N_2C
    c. Scrubbers absorb NO_2 or N_2O
    d. Scrubbers operate at 100 to 120°F
    e. Expensive technique (ozone, chlorine dioxide production, disposal of discharges)
    f. May be useful for combined NO_X, SO_X, particulate control

I. Give examples of fluidized bed combustion units which produce low NO_X
    1. Solid waste and sewage sludge incineration
    2. Hog fuel combustion
    3. Coal-fired utility boiler, 30 MW electricity (Monongahela Power Co., Rivesville, West Virginia)
    4. Coal-fired industrial boiler, 100,000 lb steam/hr (Georgetown University, Alexandria, Virginia)

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Improved Performance by Combustion Modifications

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: J. T. Beard
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 28

Lesson Goal: The goal of this lesson is to provide the student with an introduction of the state of the art combustion modification techniques which are useful in reducing air pollutant emissions.

Lesson Objectives: At the end of this lesson the student will be able to:

state the benefits of proper maintenance and adjustment of residential oil combustion units;

list three important features to check during the maintenance of commercial oil-fired burners;

discuss the difference between "minimum O_2" and "lowest practical O_2" and why these are important in industrial boilers;

list two reasons why a burner may have a higher "minimum O_2" level than the typical value and describe what remedies may be available;

indicate the effect on thermal efficiency of the combustion modification techniques: lowering excess air, staged air combustion, reduced combustion air preheat, and flue gas recirculation; and

discuss why NO_x control from coal-fired utility boilers is more difficult than from similar oil or gas units.

Student Prerequisite Skills: 427 Course, Lessons No. 17, 18, 22, and 27

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide Projector
2. Slide set for Lesson 28

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 17.

2. "Guidelines for Residential Oil-Burner Adjustments," Report No. EPA-600/2-75-069-a, Industrial Environmental Research Laboratory, USEPA (Oct. 1975).

3. "Guidelines for Burner Adjustments for Commercial Oil-Fired Boilers," Report No. EPA-600/2-76-008, Industrial Environmental Research Laboratory, USEPA (March 1976).

4. "Guidelines for Industrial Boiler Performance Improvement," Report No. EPA-600/8/77-003a, Industrial Environmental Research Laboratory, USEPA (Jan. 1977).

5. "Reference Guideline for Industrial Boiler Manufacturers to Control Pollution with Combustion Modification," Report No. EPA-600/8-77-003b, Industrial Environmental Research Laboratory, USEPA (Nov. 1977).

6. "Control Techniques for Nitrogen Oxides Emissions from Stationary Sources," Second Edition, Report No. EPA-450/1-78-001, Office of Air Quality Planning and Standards, USEPA (Jan. 1978).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 28: IMPROVED PERFORMANCE BY COMBUSTION MODIFICATION
427-28-1	SMOKE-CO_2 PLOT FOR RESIDENTIAL OIL BURNERS
427-28-2	"LOWEST PRACTICAL CO_2", RESIDENTIAL BURNERS
427-28-3	EFFECT OF STACK TEMPERATURE AND CO_2 ON THERMAL EFFICIENCY
427-28-4	USUAL RANGE OF VISCOSITY FOR OIL FIRING
427-28-5	SMOKE-CO_2 CURVE FOR COMMERCIAL RESIDUAL OIL FIRED BURNER
427-28-6	MAXIMUM DESIRABLE BACHARACH SMOKE NUMBER
427-28-7	PERCENT CO_2 IN FLUE GAS AS FUNCTION OF EXCESS AIR
427-28-8	BOILER EFFICIENCY LOSS CHANGE WITH EXCESS O_2
427-28-9	SMOKE-O_2 CURVE FOR COAL OR OIL-FIRED INDUSTRIAL BOILER
427-28-10	CO-O_2 CURVE FOR GAS-FIRED INDUSTRIAL BOILER
427-28-11	EFFECT OF EXCESS O_2 ON NO_X EMISSIONS
427-28-12	TYPICAL RANGE OF MINIMUM EXCESS O_2 AT HIGH FIRING RATES
427-28-13	EFFECT OF REDUCING THE EXCESS AIR ON BOILER EFFICIENCY
427-28-14	STAGED AIR EXPERIMENTAL WATER TUBE BOILER, TOP VIEW
427-28-15	STAGED AIR EXPERIMENTAL WATER TUBE BOILER, SIDE VIEW
427-28-16	REDUCTION OF TOTAL NO_X BY STAGED AIR WITH NATURAL GAS FUEL
427-28-17	REDUCTION OF TOTAL NO_X BY STAGED AIR WITH NO. 6 FUEL OIL
427-28-18	EFFECT OF NO_X PORTS ON BOILER EFFICIENCY
427-28-19	EFFECT OF COMBUSTION AIR TEMPERATURE ON NO_X WITH OIL AND GAS
427-28-20	INFLUENCE OF AIR PREHEAT ON NO_X
427-28-21	EFFECT OF COMBUSTION AIR PREHEAT ON BOILER EFFICIENCY

SLIDE NUMBER	TITLE OF SLIDE
427-28-22	REDUCTION IN NO_X BY FLUE GAS RECIRCULATION
427-28-23	NO_X FROM GAS, TANGENTIALLY-FIRED UTILITY BOILERS
427-28-24	EFFECTS OF NO_X CONTROL METHODS ON A GAS, WALL-FIRED UTILITY BOILER
427-28-25	EFFECT OF NO_X CONTROL METHODS ON AN OIL, WALL-FIRED UTILITY BOILER
427-28-26	NO_X FROM RESIDUAL OIL, TANGENTIALLY-FIRED UTILITY BOILERS
427-28-27	EFFECT OF BURNER STOICHIOMETRY ON NO_X IN TANGENTIAL, COAL-FIRED BOILERS

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Improved Performance by Combustion Modification

NOTES

- I. Introduction
  - A. State the lesson objectives
  - B. Review the changing emphasis of preventive maintenance for combustion equipment
    - 1. Prior to mid-1960's
    - 2. Influence of air pollution regulation changes in early 1970's
    - 3. Changes due to the "energy crisis of 1973"
- II. Residential oil-burner
  - A. Introduce the need for maintenance and adjustments
    - 1. Improve overall thermal efficiency and
    - 2. Minimize smoke, particulate, CO, and hydrocarbon emissions
  - B. Discuss annual maintenance by a skilled technician
    - 1. Recommend annual replacement of nozzle
      - a. Slight wear of soft brass nozzle causes change of spray pattern
      - b. Deposits of foreign materials cause drop size and spray pattern changes
      - c. Oversizing causes short cycling, lower thermal efficiency, higher pollutant emissions
    - 2. Clean dirt and lint from burner blast tube, from housing, and blower wheel
    - 3. Seal any combustion chamber air leaks
    - 4. Adjust electrodes for proper ignition
    - 5. Check pump pressure and reset to manufacturer's specification if necessary
  - C. Describe features of EPA recommended air adjustments
    - 1. Use proper instruments
      - a. Bacharach smoke tester
      - b. Orsat or Fyrite apparatus for CO_2 measurements
      - c. Draft guage to set barometric draft regulator
    - 2. Establish and examine a smoke-CO_2 plot for a given unit — Slide 427-28-1
      - a. Readings at various air gate settings
      - b. Locate the "knee" of the curve
      - c. Adjust air setting for a CO_2 level 1/2 to 1% lower than the CO_2 level of the "knee"
    - 3. Compare results with the standards — Slide 427-28-2
      - a. The smoke level not greater than No. 2
      - b. CO_2 level not less than the table value
      - c. Deviation can be caused by air leakage or poor air/fuel mixing
    - 4. Measure stack temperature — Slide 427-28-3
      - a. Compute the net stack temperature
        - (1) Thermometer reading minus room air temperature
      - b. Compare with recommendations
        - (1) Should not exceed 400 to 600°F for matched-package units or 600 to 700°F for conversion burners
        - (2) Excessive firing generates too much energy for heat exchanger, poor efficiency

III. Commercial oil-fired boiler
  - A. Recommend maintenance by skilled technician:
    - 1. Clean heat transfer surfaces, flue passages, and burner. Seal any air leaks.
    - 2. Confirm that the nozzle is recommended by manufacturer.
    - 3. Confirm that the oil fired is suitable.
    - 4. Check manufacturer's recommended oil temperature or viscosity range — Slide 427-28-4
  - B. Discuss EPA air adjustment technique
    - 1. Similarity to recommendations for residential units
    - 2. Establish smoke-CO_2 plot at maximum firing rate — Slide 427-28-5
    - 3. Adjust air setting for CO_2 about ½% lower than knee value
    - 4. Compare results with standards — Slide 427-28-6
      - a. Smoke level below "maximum desirable"
      - b. CO_2 level at 12% or higher
      - c. Differences caused by poor atomization or fuel-air mixing
    - 5. Special adjustments for modulating burners
      - a. Apply above at low-firing and intermediate firing
      - b. Optimum air setting at low-firing has lower CO_2 than at high-firing
    - 6. For gas firing
      - a. CO_2 level will be lower — Slide 427-28-7
      - b. Check CO reading
      - c. Set to be below 400 ppm
    - 7. Check stack temperature

IV. Industrial boiler adjustments
  - A. Describe how proper maintenance and adjustment for lowest practical excess oxygen can achieve
    - 1. Reduced NO_x emissions and
    - 2. Improved overall thermal efficiency — Slide 427-28-8
      - a. As excess oxygen reduced in coal and oil-fired industrial units, "smoke limit" or "minimum O_2 level" is reached — Slide 427-28-9, Slide 427-28-10
      - b. As excess oxygen reduced on a natural gas-fired unit, a "CO limit" or "minimum O_2 level" is reached (400 ppm CO)
  - B. Describe that lowest practical excess oxygen is greater than the minimum excess oxygen to accommodate:
    - 1. Rapid burner modulation
    - 2. "Play" in automatic controls
    - 3. Variation in ambient conditions (mainly atmospheric pressure, if boiler room provides constant temperature and shielding from ambient wind), and
    - 4. Variation in fuel properties
  - C. Review NO_x control through reducing excess air — Slide 427-28-11
    - 1. NO_x from coal combustion is very sensitive to excess oxygen
    - 2. NO_x from fuel oil combustion is sensitive to excess oxygen, and

3. NO_X from natural gas combustion is lower than from oil or coal and is less sensitive to excess oxygen
4. Fuel NO_X is very sensitive to excess air (example: coal and fuel oil units)
5. Thermal NO_X is not always reduced with less excess air (example: NO_X from natural gas units may increase with decreased excess air)

D. Describe features of the EPA step-by-step boiler adjustment procedure
  1. Differences between this procedure and those for residential and commercial units
    a. Sophistication of combustion control and safety on industrial units
    b. Instrumentation (continuous monitors for excess O_2 or CO_2, CO, NO_X, opacity, and stack temperature),
    c. Importance of sampling site for representative measurement and
    d. Boiler load characteristics requiring siderable burner modulation
  2. Compare "minimum O_2" level with typical values — Slide 427-28-12
    a. Too high a minimum value results from burner malfunctions or other fuel or equipment-related problems and
    b. Many burners exhibit higher "minimum O_2" at lower firing rates
  3. Thermal efficiency is increased
    a. Care should be exercised to avoid CO, hydrocarbon, and smoke — Slide 427-28-13

V. Industrial boiler design changes
  A. Manufacturer may adopt design modifications for NO_X control which will provide
    1. Lowering of excess air and improved boiler efficiency
    2. Staged combustion with lower boiler efficiency
    3. Reduced combustion air preheat temperature with reduced boiler efficiency
    4. Flue gas recirculation with a small degradation in efficiency
  B. Give an example of the influence of staged combustion (from 40,000 lb/hr water-tube boiler);
    1. Special secondary overfire air ports (NO_X ports) — Slide 427-28-14, 15
    2. Burners operated with less than stoichiometric air (e.g., 95%) — Slide 427-28-16; Slide 427-28-17
    3. Location and air velocity of NO_X ports important for maximum NO_X control
    4. Thermal efficiency reduced usually — Slide 427-28-18
  C. Give examples of reduced combustion air preheat temperature (three boilers using natural gas or No. 6 fuel oil) which is — Slide 427-28-19
    1. Effective NO_X control for gas and oil
    2. Not effective for NO_X control in coal-firing (unless high excess air is required) — Slide 427-28-20

3. Typically lower thermal efficiency since flue gas temperatures increase when air preheaters not used

Slide 427-28-21

D. Give an example of flue gas recirculation (FGR)

Slide 427-28-22

1. An effective technique for NO_X control, particularly for natural gas fuel
2. Effect depends on the percent of flue gas recirculated
3. Delivered with the primary air, the secondary air, or the total air, appear combustion equipment
4. May not be the cost-effect method of NO_X control

VI. Utility boilers

A. Emphasize that NO_X control effectiveness varies with
1. Furnace characteristics (size, shape, and operational flexibility)
2. Fuel/air handling systems and automatic controls
3. Operational problems resulting from combustion modification
   a. Emission of other pollutants (CO, smoke, carbon in flyash)
   b. Onset of slagging and fouling
   c. Incipience of flame stability

B. Describe combustion modification examples for gas-fired utility boilers
1. Produce only thermal NO_X, the easiest to control by combustion modification

Slide 427-28-23

2. Low excess air, routinely used in gas-fired utility boilers for NO_X control whose
   a. Reduction depends on furnace design and firing method
   b. Flame stability is not a serious problem
   c. Slight increase in thermal efficiency is generally noted
3. Flue gas recirculation (up to 20%) produces substantial NO_X control (20 to 60%)

Slide 427-28-24

4. Overfire air, biased firing, burners-out-of-service are effective techniques for achieving NO_X control by off-stoichiometric combustion
5. Larger units produce more NO_X because of higher combustion temperature

C. Describe combustion modification examples for oil-fired utility boilers using
1. Fuel NO_X, important part of the total NO_X
2. Low excess air, routine in oil-fired burners for NO_X control
3. Overfire air ports, an accepted technique for providing two-stage combustion in wall-fired units

Slide 427-28-25

4. Burners-out-of-service in the upper part of the firing pattern, used for NO_X control in wall and tangentially fired oil units.

5. Two-stage combustion with flue-gas recirculation
    a. Gives NO_X reductions of 40 to 60%, but
    b. May require de-rating to be successful
6. Larger units do not appear to produce more NO_X (fuel NO_X rather than thermal NO_X in oil-fired units) — Slide 427-28-26
7. Flame stability problems occur with flue-gas recirculation (higher burner velocities)
8. Boiler cleanliness problems (deposits in the radiant section) can increase NO_X by 50 ppm

D. Describe combustion modification examples for coal-fired utility boilers whose
1. Fuel-bound nitrogen accounts for up to 80% of the NO_X from burning coal
2. Wall-fired burners obtain reduced NO_X through modifications such as
    a. Low excess air
    b. Staged firing
    c. Load reduction
    d. Flue-gas recirculation, which is much less effective with coal-firing than with oil or gas
3. Tangentially-fired boilers emit less NO_X than wall-fired boilers with — Slide 427-28-27
    a. Off-stoichiometric firing, effective for NO_X control
    b. Fuel-rich burner conditions which can produce excessive smoke and CO and flame instability
4. Flue-gas treatment may be a potential NO_X control technique for coal combustion in the future

NOTE: These techniques were discussed in Lesson 27.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Waste Gas Flares

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: F. A. Iachetta
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 29

Lesson Goal: The goal of this lesson is to provide the student with engineering information on the application of flares to control hydrocarbon and toxic gaseous emissions.

Lesson Objectives: At the end of this lesson the student will be able to:

calculate the carbon-to-hydrogen ratio of a waste gas stream and determine when and how much steam will be required for smokeless flare operation;

understand the difference between elevated and ground-level flares and the design considerations which underlie the choice of one or the other; and

describe provisions for leveling waste gas flow rates from intermittent sources.

Student Prerequisite Skills: Course 427, Lessons 3, 5, and 7.

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector
2. Slide set for Lesson 29.

Special Instructions: Optional Topic 1

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 14.

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 29: WASTE GAS FLARES
427-29-1	GAS PROPERTIES RE-FLARING
427-29-2	GAS PROPERTIES RE-FLARING
427-29-3	SMOKE TENDENCIES, ACETYLENE
427-29-4	SMOKE TENDENCIES, PROPANE
427-29-5	SMOKE TENDENCIES, ETHANE
427-29-6	SMOKE TENDENCIES, $H/C \geq 0.28$
427-29-7	WATER-GAS REACTIONS
427-29-8	STEAM REQUIREMENTS FOR SMOKELESS FLARE
427-29-9	JOHN ZINK SMOKELESS FLARE TIP
427-29-10	CROSS SECTION OF A SMOKELESS FLARE BURNER
427-29-11	FLARE TIP WITH INTERNAL STEAM INJECTION
427-29-12	SINCLAIR FLARE BURNER
427-29-13	ESSO TYPE BURNER
427-29-14	MULTISTREAM-JET BURNER
427-29-15	MULTIJET-GROUND FLARE
427-29-16	VENTURI-TYPE FLARE
427-29-17	WATER SPRAY TYPE GROUND FLARE
427-29-18	NUMBER OF PILOTS REQUIRED

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Waste Gas Flares

Page 3 *of* 4

NOTES

I. Introduction
  A. State lesson objectives
  B. Discuss the general background of flare combustion as an air quality control method
    1. Flares are used to dispose of waste gases
    2. Gases which may be flared:
      a. Need concentrations greater than the L.F.L.
      b. Particulates can be dangerous; discuss why and how

Slide 427-29-1, 2 refer to Student Manual, p. 14-31.

II. Various Flare Designs
  A. Describe the types of flares
    1. Pit type, usually not desirable
    2. Ground-level flares
      a. These are usually limited to lower molecular weight gases
      b. There is a need for thermal radiation shielding; describe it
      c. Operational features, such as relatively easier maintenance and less visibility can be had with some flare designs
    3. Elevated flares are used with heavier molecular weight gases
      a. The elevated flare also is used when combustion products are relatively undesirable
      b. Flare elevation reduces or eliminates the need for thermal radiation shielding — an economic advantage
    4. The use of water-surge tanks to dampen flow fluctuations
  B. Describe flare combustion characteristics
    1. The importance of the H/C ratio for smokeless operation should be emphasized
      a. $H/C > 0.28$ requires no steam
      b. $H/C < 0.28$ requires steam for smokeless operation

Slide 427-29-3
Slide 427-29-4
Slide 427-29-5
Slide 427-29-6

    2. Water gas or shift reactions

Slide 427-29-7

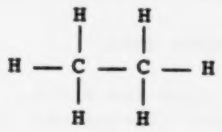
$$C + H_2O \rightarrow CO + H_2$$

$$C + 2H_2O \rightarrow CO_2 + H_2$$

    3. There are limitations on the use of liquid water sprays instead of steam
    4. The conditions governing the use of steam should be evaluated
      a. The importance of H/C ratio should be restated
      b. The degree to which hydrocarbons may be saturated or unsaturated should be mentioned

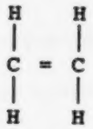
Slide 427-29-8 or refer to Student Manual, Attachment 14-14, p. 14-26.

c. Examples are:
ethene, C_2H_6, all single bonds for carbon, saturated with hydrogen


$$\mathrm{H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-H}$$

C_2H_6

and ethylene, C_2H_4, unsaturated as indicated by a double bond


$$\mathrm{\overset{\displaystyle H}{\underset{\displaystyle H}{C}}=\overset{\displaystyle H}{\underset{\displaystyle H}{C}}}$$

C_2H_4

d. Conditions for minimum steam must be noted.

5. The details of various flares, noting that steam can be introduced in many different ways — Slide 427-29-9
   a. Slides 427-29-6 through 427-29-10 illustrate various arrangements — Slide 427-29-10
Slide 427-29-11
Slide 427-29-12
Slide 427-29-13
Slide 427-29-14
   b. Light gases (H/C > .28 or CO rich) can be flared in either a venturi or a multijet flare arrangement — Slide 427-29-15
   c. Water sprays can be used with heavy gases in ground flares — Slide 427-29-16
   d. A range of flare diameters should be given — Slide 427-29-17 or refer to Student Manual, p. 14-24.
   e. The number of pilots required is a function of flare diameter — Slide 427-29-18
   f. The allowable radiation of 1,000 Btu/ft^{2}hr can be used as a design criterion
      (i) Usually solar input of 300 Btu/ft^{2}hr has to be taken into account

6. Noise problems arise both from combustion and the use of steam.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Municipal Sewage Sludge Incineration

COURSE: 427, Combustion Evaluation
LESSON TIME: 50 min.
PREPARED BY: J. T. Beard
DATE: Aug. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 30

Lesson Goal: The goal of this lesson is to provide the student with information about the design, operation, and air pollution emissions from sewage sludge incinerators.

Lesson Objectives: At the end of this lesson the student will be able to:

list and discuss the air pollutants emitted in the incineration of sewage sludge;

describe the special design features required for burning wet sewage sludge fuel;

describe the combustion-related activity occurring in each of the four zones of the multiple-hearth sewage sludge incinerators;

discuss the options of combustion air preheating, flue gas reheating, and energy recovery; and

list two important operational problems which can adversely influence air pollution emissions.

Student Prerequisite Skills: Course 427, Lessons Number 23 and 26

Level of Instruction: Undergraduate engineering or equivalent

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

1. Slide projector

2. Slide set for Lesson 30

Special Instructions: None

References:

1. Combustion Evaluation in Air Pollution Control, Chapter 12.

2. "Air Pollution Aspects of Sludge Incineration," EPA Technology Transfer Seminar Publication, EPA-625/4-75-009 (June 1975).

3. Petura, R. C., "Operating Characteristics and Emission Performance of Multiple Hearth Furnaces with Sewer Sludge," Proceeding of 1976 National Waste Processing Conference, ASME, pp. 313-327 (May 1976)

4. Rubel, F. N., Incineration of Solid Wastes, Noyes Data Corp. Park Ridge, N.J. (1974).

SLIDE NUMBER	TITLE OF SLIDE
	LESSON 30: MUNICIPAL SEWAGE SLUDGE INCINERATION
427-30-1	TYPICAL SECTION OF A MULTIPLE-HEARTH SLUDGE INCINERATOR
427-30-2	MULTIPLE-HEARTH FURNACE FOR INCINERATING MUNICIPAL SEWAGE SLUDGE
427-30-3	SINGLE HEARTH SLUDGE FURNACE
427-30-4	FUNDAMENTALS OF FLUIDIZED INCINERATION

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Municipal Sewage Sludge Incineration

NOTES

I. Introduction
   A. State the lesson objectives
   B. Incineration is an acceptable method for sludge reduction to produce
      1. Sterile landfill material
      2. Odorless emissions
   Particulates may be controlled to the New Source Performance Standards (1.3 lb/ton dry sludge input) by using either
      1. Venturi scrubbers with approximately 18 inches of water pressure drop
      2. Impingement scrubbers and automatic control (sensing O_2) of auxiliary fuel burners or
      3. Electrostatic precipitators

II. Municipal Sewage Sludge
   A. Describe composition and give examples of
      1. Moisture content
         a. Varies with ratio of primary to secondary treatment
         b. Varies with drying equipment
      2. Combustible materials
      3. Dry heat content

See Attachment 12-1, Chapter 12 page 12-10

   B. May contain metals, potentially hazardous air pollutants
      1. Give examples which are converted to oxides and removed with ash or particulates (cadmium, lead, magnesium, and nickel)
      2. Describe special problems of mercury
         a. Provide an example concentration (5 ppm)
         b. Decomposes to mercuric oxide or metallic mercury in high-temperature regions of incinerators
         c. Give an example of removal by scrubbers
         d. State the hazardous pollutant standard limiting mercury from incineration and sludge drying facilities (3,200 g/day)
   C. Discuss toxic pesticide content, as well as other organic compounds, such as PCB's
      1. Give an example concentration (1.2 to 2.5 ppm)
      2. State influence of combustion temperature on decomposition
         a. Up to 95% at 700°F
         b. Total decomposition at 1,100°F

III. Multiple-Hearth Furnaces
   A. Describe history of use
      1. Current design, an adaptation of the Herreshoff design of 1889

Slide 427-30-1

      2. Previously used for roasting ores
      3. Adapted for sewage sludge in 1930's
         a. Oil-fired auxiliary fuel
         b. Manual operation controls
      4. Wet scrubbers added in 1960's
      5. Automatic controllers, improved in the 1970's
   B. Describe typical design features
      1. Cylindrical refractory lined shell

CONTENT OUTLINE

Course: 427, Combustion Evaluation
Lecture Title: Municipal Sewage Sludge Incineration

Page 5 of 6

NOTES

2. Multiple (5 to 11) horizontal refractory hearths
3. Mechanical stoking produced by motor-driven revolving central shaft:
    a. Typically, 2 or 4 "ramble" arms for each hearth
    b. Central shaft and "ramble" arms, air cooled
    c. "Ramble" teeth (similar to ploughs) agitate the sludge material and move it across hearth to openings for passage to the next lower hearth
    d. Plowing breaks up lumps and exposes fresh area to heat and oxygen
4. Excess air, between 50 and 125%

C. Discuss temperatures and purposes of each combustion zone
1. Drying zone
    a. Moisture reduced to 45 or 50%
    b. Sludge temperatures raised from ambient to 160°F
    c. Gases cooled to around 850°F
    d. Typically no odor problem because of low sludge temperature
2. Volatilization zone
    a. Distillation of volatiles
    b. Combustion of gases, yellow flame
    c. Temperatures 1,300 to 1,700°F
3. Fixed carbon burning zone
    a. Short blue flame
4. Cooling zone
    a. Cooling ash heats combustion air

D. Discuss influence of moisture on combustion and fuel requirements
1. Give an example of the influence of moisture content on combustion temperature
2. Give examples of influence of moisture and feed rate on combustion zone location
    a. Feed rate or moisture reduced, combustion region may move to higher hearth
    b. Feed rate or moisture increased, combustion region may move to lower hearth, because longer drying time is required
    c. If combustion zone drops too low, auxiliary fuel must provide energy to control combustion zone

E. State that instrumentation and combustion control systems may include
1. Temperature-indicating controllers
2. Proportionate fuel burners (with electric ignition)
3. Ultraviolet scanners
4. Motorized valves in air headers
5. Automatic draft control
6. Flue-gas oxygen analyzer driven controller

F. State that cooling air (at 400°F) from central shaft and "ramble" arms may be used as

Slide 427-30-2

1. Preheated combustion air
2. Reheat energy to aid in dissipating the plume associated with the wet scrubbers

G. Describe waste heat recovery designs

1. Combustion air preheat
2. Building environmental control or
3. Thermal conditioning of sewage sludge (to reduce moisture and save fuel costs)

H. Review methods for controlling air pollutant emissions
  1. Insufficient combustion air results in smoke emitted from furnace doors as well as stack
  2. Plugged scrubber plates will cause restriction of gas flow
  3. Venturi scrubber recommended
  4. Auxiliary fuel burners for combustion temperature
  5. Sludge dewatering for combustion temperature
  6. Afterburner for
    a. Plume dispersion
    b. Odor control

IV. Other municipal sewage sludge incineration equipment
  A. Mention, as an example, the design of small single-hearth sludge furnaces — Slide 427-30-3
  B. Discuss the typical design features and emissions control of fluidized-bed combustion units (reactors) — Slide 427-30-4
    1. Fluid bed where fuel, sand, and residual inorganic materials are intimately mixed with air (resembles boiling agitation)
    2. Thermal oxidation (at 1,200 to 1,920°F) with no flame, bed may glow
    3. Fluid bed volume of adequate size to act as a stabilizing heat sink
    4. Disengagement zone above fuel bed which permits larger solid particles to settle out before exiting with the flue gases
    5. Scrubber required for particulate control
    6. Operating temperatures and excess air are low so that NO_X formation is modest
    7. Also demonstrated with wood waste and with liquid chemical to produce hot gases for steam generation in recovery boiler
  C. Mention that co-firing of municipal solid waste with sludge has been proposed as an acceptable combustion plan having improved economy.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: Pre-Test and Post-Test

COURSE: 427, Combustion Evaluation
LESSON TIME: 60 min.
PREPARED BY: DATE:
J. T. Beard Oct. 1978

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Lesson Number: 31

Lesson Goal: The goal of the Pre-Test and Post-Test is to measure the effectiveness of the training program in teaching the participants the instructional objectives.

Lesson Objectives: At the end of the time periods for the Pre-Test or the Post-Test, the student will have:

determined to the best of his or her ability the correct answers to the 50 questions on the test;

worked the test independently without assistance from other persons, from personal notes, or from other course or text materials;

marked his or her answers on the answer sheet, signed the answer sheet; and

handed the answer sheet to the course moderator.

Student Prerequisite Skills: Air Pollution Training Institute Course 452 or equivalent experience, and one of the following: college level training in physical science, engineering, or mathematics.

Level of Instruction: Undergraduate engineering or equivalent.

Intended Student Professional Backgrounds: Engineers, technical staff, regulatory officials, and others who work in combustion-related areas of air pollution control.

Support Materials and Equipment:

Multiple copies of Pre-Test and Post-Test, including the attached tables of property values and answer sheets, for distribution to the students at the beginning of the testing period.

Special Instructions:

Advise the students that the tests are timed, closed-book tests, and that only the completed answer sheet is to be handed in at the end of the test time period.

The Pre-Test measures the students' entrance level of knowledge about Combustion Evaluation in Air Pollution Control; and the Post-Test measures the students' knowledge at the end of the course. A comparison of the students' grades on the two tests will indicate the learning that has been achieved during the training period.

A completed answer sheet is included in the lesson plan to aid the course moderator in grading the tests. At the end of the tests the moderator may post the answer sheet for the benefit of the students.

Reference: None

ANSWER SHEET for Pre-Test
#427 — Combustion Evaluation

SCORE FOR PRE-TEST

Name: ______________________________

Part I True-False

1. [✓ T] F
2. T [✓ F]
3. [✓ T] F
4. [✓ T] F
5. T [✓ F]
6. T [✓ F]
7. [✓ T] F
8. T [✓ F]
9. T [✓ F]
10. [✓ T] F

Part II Multiple Choice

1. a [✓ b] c d
2. a b [✓ c] d
3. [✓ a] b c d
4. a b [✓ c] d
5. a b [✓ c] d
6. a b c [✓ d]
7. [✓ a] b c d
8. a b c [✓ d]
9. [✓ a] b c d
10. a b c [✓ d]
11. a b c [✓ d]
12. a b c [✓ d]
13. a b [✓ c] d
14. a b c [✓ d]
15. a b [✓ c] d
16. a b [✓ c] d

Part II (continued)

17. a b c [✓ d]
18. a [✓ b] c d
19. a [✓ b] c d
20. a b [✓ c] d
21. a [✓ b] c d
22. a b c [✓ d]
23. a [✓ b] c d
24. a b c [✓ d]
25. a [✓ b] c d

Part III Fill in the Blank

1. 100°F
2. ∿ 1,000 Btu/ft^3
3. ∿ 84% ± 5%

4.a utility or industrial power plants

b diesel engines; gas turbines

5.a nozzle — (is it appropriate?)

b oil — (is it appropriate? what T?)

6.a sulfur; nitrogen;

b ash; vanadium

7. steam injection

Part IV Problems

1. 2.38 ft^3
2. 25,000 ft^3
3. 674 gal/hr
4. 5,801 Btu/lb
5. 22 %

#427 — COMBUSTION EVALUATION IN AIR POLLUTION CONTROL

PRE-TEST

Note: The entire test is closed book. Each answer is worth 2 points. Enter all answers on the ANSWER SHEET provided.

Part I True-False

Note: For each of the following statements, circle on the answer sheet the letter T if the statement is True or the letter F if False.

1. T F Good combustion with minimum oxygen and no CO in the flue gas implies maximum thermal efficiency.
2. T F A gas flame is likely to develop a yellow tip with increased percent premix.
3. T F Excess air can be used to control furnace temperature.
4. T F The use of water walls in a furnace permits reduction of excess air relative to a refractory-wall furnace.
5. T F Most gas burners can easily handle a wide spectrum of gaseous fuels.
6. T F The difference between the higher (gross) and the lower (net) heating value of any fuel is the amount of heat lost to the surroundings of the combustion installation.
7. T F At chemical equilibrium the forward and reverse reactions are equal with the net effect of no change in the amounts of reactants present.
8. T F The region of stable flame operation is unaffected by the fuel gas flow rate through a burner.
9. T F Furnace volume required for burning gaseous fuels is generally higher than for the more dense fuels, such as oil or coal.
10. T F Blue flame is characteristic of burning gaseous fuels with a high degree of premix of the fuel and the air.

Part II Multiple Choice

Note: There is only one "best answer." Circle the proper letter on the answer sheet.

1. The major limit on the rate of combustion of a fuel oil is

   a the rate of mixing of the air and fuel vapor.
   b the rate of vaporization of the oil.
   c the rate of diffusion of O_2 to the surface of the droplet.

2. Combustion rate is influenced by the temperature as expressed by

   a Charles' Law.
   b Dalton's Law.
   c the Arrhenius Equation.

3. The heat content or enthalpy of a material is

   a the sum of sensible and latent heats above some reference condition.
   b the sum of gross heating value and the sensible and latent heats above a reference value.
   c the sum of the available heat and the sensible and latent heat above the reference value.

4. As the temperature of a fuel oil increases

   a the fuel oil number increases.
   b viscosity increases.
   c viscosity decreases.
   d more pumping energy is required.

5. The oil vapor temperature at which a spark will cause ignition (explosion) is called

   a lower flammability limit.
   b higher flammability limit.
   c flash point.
   d fire point.

6. Smoke may be reduced from a controlled-air incinerator by

   a opening the charging door.
   b adding moisture to the charge.
   c increasing the fan speed.
   d reducing the charging rate and air velocity.

7. Sulfur from fuel oil combustion

   a is shifted more to SO_3 with higher excess air
   b is emitted mainly as SO_3 mist.
   c does not contribute to the heating value of the fuel.
   d is desirable because it kills germs.

8. Catalytic dissociation

   a is recommended for controlling NO_x from coal furnaces.
   b requires an oxidizing atmosphere.
   c requires a carefully controlled high gas temperature.
   d requires a reducing atmosphere.

9. The theoretical minimum flue gas temperature which can be achieved from a boiler producing 500°F steam, which has a preheater and an economizer, is

a ambient temperature.
b 500°F.
c 1,000°F x efficiency.
d 500°F x efficiency.

10. Improper operation of a natural gas fuel boiler is indicated by an instrument reading of

a 10% O_2 in the flue gas.
b 2% CO in the flue gas.
c opacity of 30%.
d all of the above.

11. Which of the following formulas would you use to calculate (at constant pressure) a volume change in flue gases due to changes in flue gas temperature?

a $Q = \text{Sp. heat} \times \text{lbs} \ (T_2 - T_1)$.

b $HA_2 = \frac{HA}{HV_g} \times HV_g$

c $\frac{V_1}{t_1} = \frac{V_2}{t_2}$ t = centigrade temperature

d $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ T = absolute temperature

12. Flue gas oxygen content

a may be used as a combustion control variable.
b is particularly useful when a system simultaneously burns multiple fuels.
c can be used in the place of CO_2 to monitor combustion.
d all of the above.

13. A certain mass of methane occupies 100 ft^3 at 60°F and 1 atm. pressure. The temperature and pressure of this gas is raised to 580°F and 2.5 atm. The volume of methane at the final conditions is

a greater than 100 ft^3.
b equal to 100 ft^3.
c less than 100 ft^3.

14. The volatile matter in solid fuel has the greatest influence on which of the following?

   a total air required.
   b fuel bed thickness.
   c combustion temperature.
   d overfire air.

15. Water injection is an effective NO_X control measure for gas turbines because

   a gas turbines operate at higher temperatures than furnaces.
   b water is cheap and weighs about the same as oil.
   c water acts as a heat sink.
   d water helps to wash away the soot.

16. Flue gas recirculation generally

   a improves the thermal efficiency.
   b increases the combustion temperature.
   c reduces the combustion temperature.
   d is more effective for fuel NO_X than for thermal NO_X.

17. The effect of a substantial increase in the fuel moisture content

   a reduces flame temperature.
   b reduces energy utilization in the radiant boiler section.
   c reduces rated unit capacity.
   d all of the above.

18. Multiple-chamber incinerators operate with _____ excess air, compared to controlled-air incinerators.

   a less
   b more
   c higher temperature
   d lower velocity

19. Combustion in controlled-air incinerators occurs

   a with lower temperatures than in multiple-chamber units.
   b with low velocities.
   c with three stages of combustion.
   d with more particulate emissions than a municipal incinerator equipped with a water-spray device.

20. Most toxic and hazardous chemicals

   a cannot be disposed of by incineration.
   b have general-purpose incinerators available for their destruction.
   c require specially designed incinerators.

21. Afterburners are operated at less than 25 percent of LEL concentration of combustibles

  - a to avoid excessive temperatures.
  - b for safety reasons.
  - c due to availability of low-cost fuels.

22. A flue-fed single-chamber incinerator with an afterburner on the roof, in comparison to a controlled-air incinerator

  - a has less fuel required by the afterburner.
  - b needs a larger fan.
  - c has lower average air velocities.
  - d uses more overall excess air.

23. Steam-atomizing nozzles may be converted to air-atomizing nozzles

  - a because air is so economical.
  - b if the fuel temperature and viscosity are appropriate.
  - c if the nozzles get dirty.
  - d only in commercial-sized oil-fired units.

24. F-factors

  - a are useful in calculating concentrations from new stationary sources.
  - b do not require actual air-flow and fuel-flow values.
  - c do require correction for excess air.
  - d all of the above.

25. The emission factors, such as those given in AP-42, are

  - a exact for each type of source indicated.
  - b the average emissions from a collection of similar sources.
  - c valid only for new equipment.
  - d all of the above.

Part III Fill in the Blanks

1. State the typical flash point for a No. 2 fuel oil: _______ $^{\circ}$F.

2. Give a representative value of the heat of combustion for a natural gas:

______________ Btu/scf.

3. State a typical percentage by weight of methane in natural gas: ___________ %.

4. List two of the three major stationary sources of NO_x emissions:

  a ____________________

  b ____________________

5. List two important features that should be checked during maintenance of commercial oil-fired boilers:

a ____________________

b ____________________

6. List two chemical constituents in a fuel which influence the air pollutants formed:

a ____________________

b ____________________

7. The water-gas reaction in flare combustion is achieved by __________________.

Part IV Problems

1. If one ft^3 of hydrogen at standard conditions requires the oxygen from 2.38 ft^3 of air for complete combustion, the air required to burn one ft^3 of CO will be: _______________ ft^3.

2. For hogged fuel having 5,000 Btu/lb as-fired heating value, calculate the furnace volume required to fire 50 ton/hr if a reasonable design is 20,000 Btu/hr ft^3: _______________ ft^3.

3. If the energy output needed is 75×10^6 Btu/hr, calculate the required oil-burning rate if API 10-degree oil is burned with an overall thermal efficiency of 72%: _______________ gal/hr.

4. If Douglas Fir has a dry heating value of 9,050 Btu/lb, calculate the as-fired heating value if the moisture as-fired is 35.9%: _______________ Btu/lb.

5. Determine the excess air percentage for a fuel combustion process whose Orsat analysis of the flue gas is 9% CO_2, 5% O_2, and 2% CO:

____________________ % excess air.

$$\%EA = \frac{(O_{2p} - 0.5\ CO_p) \times 100\%}{0.264\ N_{2p} - (O_{2p} - 0.5\ CO_p)}$$

Attachment 3-1, Analyses of Samples of Natural Gas[2]

Sample No. Source of Gas	1 Pa.	2 So. Cal.	3 Ohio	4 La.	5 Okla.
Analyses					
Constituents, % by vol					
H_2 Hydrogen	—	—	1.82	—	—
CH_4 Methane	83.40	84.00	93.33	90.00	84.10
C_2H_4 Ethylene	—	—	0.25	—	—
C_2H_6 Ethane	15.80	14.80	—	5.00	6.70
CO Carbon monoxide	—	—	0.45	—	—
CO_2 Carbon dioxide	—	0.70	0.22	—	0.80
N_2 Nitrogen	0.80	0.50	3.40	5.00	8.40
O_2 Oxygen	—	—	0.35	—	—
H_2S Hydrogen sulfide	—	—	0.18	—	—
Ultimate, % by wt					
S Sulfur	--	—	0.34	—	—
H_2 Hydrogen	23.53	23.30	23.20	22.68	20.85
C Carbon	75.25	74.72	69.12	69.26	64.84
N_2 Nitrogen	1.22	0.76	5.76	8.06	12.90
O_2 Oxygen	—	1.22	1.58	—	1.41
Specific gravity (rel to air)	0.636	0.636	0.567	0.600	0.630
Higher heat value					
Btu/cu ft @ 60F & 30 in. Hg	1,129	1,116	964	1,002	974
Btu/lb of fuel	23,170	22,904	22,077	21,824	20,160

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Attachment 3-3, Detailed Requirements for Fuel Oils[1]

Grade of Fuel Oil[b]		Flash Point, F	Pour Point, F	Water and Sediment, per cent by volume	Carbon Residue on 10 per cent Bottoms, per cent	Ash, per cent by weight	Distillation Temperatures, F			Saybolt Viscosity, sec				Kinematic Viscosity, centistokes				Grav-ity, deg API	Copper Strip Corro-sion
							10 per cent Point	90 per cent Point		Universal at 100 F		Furol at 122 F		At 100 F		At 122 F			
		Min	Max	Max	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Min	Max
No. 1	A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	100 or legal	0	trace	0.15	...	420	550	...	...	...	...	...	2.2	1.4	...	...	35	No. 3
No. 2	A distillate oil for general purpose domestic heating for use in burners not requiring No. 1 fuel oil	100 or legal	20[c]	0.10	0.35	...	[d]	640[e]	540[e]	37.93	32.6	...	...	(3.6)[e]	(2.0)[e]	...	...	30[g]	...
No. 4	An oil for burner installations not equipped with preheating facilities	130 or legal	20	0.50	...	0.10	...	...	...	125	45	...	...	(26.4)	(5.8)	...	...	...	...
No. 5	A residual-type oil for burner installations equipped with preheating facilities	130 or legal	...	1.00	...	0.10	...	...	...	...	150	40	...	...	(32.1)	(81)	...	...	...
No. 6	An oil for use in burners equipped with preheaters permitting a high-viscosity fuel	150	...	2.00[f]	...	...	...	...	...	...	...	300	45	...	...	(638)	(92)	...	...

---

[a] Recognizing the necessity for low sulfur fuel oils used in connection with heat treatment, nonferrous metal, glass, and ceramic furnaces and other special uses, a sulfur requirement may be specified in accordance with the following table.

Grade of Fuel Oil	Sulfur, max. per cent
No. 1	0.5
No. 2	1.0
No. 4	no limit
No. 5	no limit
No. 6	no limit

Other sulfur limits may be specified only by mutual agreement between the purchaser and the seller.

[b] It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

[c] Lower or higher pour points may be specified whenever required by conditions of storage or use. However, these specifications shall not require a pour point lower than 0 F under any conditions.

[d] The 10 per cent distillation temperature point may be specified at 440 F maximum for use in other than atomizing burners.

[e] When pour point less than 0 F is specified, the minimum viscosity shall be 1.8 cs (32.0 sec, Saybolt Universal) and the minimum 90 per cent point shall be waived.

[f] The amount of water by distillation plus the sediment by extraction shall not exceed 2.00 per cent. The amount of sediment by extraction shall not exceed 0.50 per cent. A deduction in quantity shall be made for all water and sediment in excess of 1.0 per cent.

[g] In the states of Alaska, Arizona, California, Hawaii, Idaho, Nevada, Oregon, Utah and Washington, a minimum gravity of 28 deg API is permissible

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Attachment 3-4, Typical Analyses and Properties of Fuel Oils[1]

Grade	No 1 Fuel Oil	No 2 Fuel Oil	No 4 Fuel Oil	No. 5 Fuel Oil	No 6 Fuel Oil
Type	Distillate (Kerosene)	Distillate	Very Light Residual	Light Residual	Residual
Color	Light	Amber	Black	Black	Black
API gravity, 60 F	40	32	21	17	12
Specific gravity, 60 60 F	0.8251	0.8654	0 9279	0 9529	0 9861
Lb per U S. gallon, 60 F	6.870	7 206	7 727	7.935	8.212
Viscos., Centistokes, 100 F	1.6	2.68	15 0	50 0	360.0
Viscos., Saybolt Univ., 100 F	31	35	77	232	—
Viscos., Saybolt Furol, 122 F	—	—	—	—	170
Pour point, F	Below zero	Below zero	10	30	65
Temp for pumping, F	Atmospheric	Atmospheric	15 min.	35 min.	100
Temp, for atomizing, F	Atmospheric	Atmospheric	25 min.	130	200
Carbon residue, per cent	Trace	Trace	2 5	5 0	12 0
Sulfur, per cent	0 1	0 4 0 7	0 4 1 5	2 0 max	2 8 max.
Oxygen and nitrogen, per cent	0 2	0 2	0.48	0 70	0 92
Hydrogen, per cent	13.2	12 7	11 9	11.7	10.5
Carbon, per cent	86 5	86.4	86.10	85.55	85.70
Sediment and water, per cent	Trace	Trace	0 5 max.	1 0 max	2 0 max.
Ash, per cent	Trace	Trace	0 02	0.05	0.08
Btu per gallon	137,000	141,000	146,000	148,000	150,000

* Technical information from Humble Oil & Refining Company.

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Attachment 3-5, Gravities, Densities, and Heats of Combustion of Fuel Oils[6]

VALUES FOR 10 TO 49 DEG API, INCLUSIVE, REPRINTED FROM BUREAU OF STANDARDS MISCELLANEOUS PUBLICATION NO. 97, "THERMAL PROPERTIES OF PETROLEUM PRODUCTS."

GRAVITY AT 60/60 F		DENSITY AT 60 F	TOTAL HEAT OF COMBUSTION (At Constant Volume)			NET HEAT OF COMBUSTION (At Constant Pressure)		
DEG API	SPECIFIC GRAVITY	LB PER GAL	BTU PER LB	BTU PER GAL AT 60 F	CAL PER G	BTU PER LB	BTU PER GAL AT 60 F	CAL PER G
5	1.0366	8.643	18,250	157,700	10,140	17,290	149,400	9,610
6	1.0291	8.580	18,330	157,300	10,180	17,340	148,800	9,650
7	1.0217	8.518	18,390	156,600	10,210	17,390	148,100	9,670
8	1.0143	8.457	18,440	155,900	10,240	17,440	147,500	9,700
9	1.0071	8.397	18,490	155,300	10,270	17,490	146,900	9,720
10	1.0000	8.337	18,540	154,600	10,300	17,540	146,200	9,740
11	0.9930	8.279	18,590	153,900	10,330	17,580	145,600	9,770
12	0.9861	8.221	18,640	153,300	10,360	17,620	144,900	9,790
13	0.9792	8.164	18,690	152,600	10,390	17,670	144,200	9,810
14	0.9725	8.108	18,740	152,000	10,410	17,710	143,600	9,840
15	0.9659	8.053	18,790	151,300	10,440	17,750	142,900	9,860
16	0.9593	7.998	18,840	150,700	10,470	17,790	142,300	9,880
17	0.9529	7.944	18,890	150,000	10,490	17,820	141,600	9,900
18	0.9465	7.891	18,930	149,400	10,520	17,860	140,900	9,920
19	0.9402	7.839	18,980	148,800	10,540	17,900	140,300	9,940
20	0.9340	7.787	19,020	148,100	10,570	17,930	139,600	9,960
21	0.9279	7.736	19,060	147,500	10,590	17,960	139,000	9,980
22	0.9218	7.686	19,110	146,800	10,620	18,000	138,300	10,000
23	0.9159	7.636	19,150	146,200	10,640	18,030	137,700	10,020
24	0.9100	7.587	19,190	145,600	10,660	18,070	137,100	10,040
25	0.9042	7.538	19,230	145,000	10,680	18,100	136,400	10,050
26	0.8984	7.490	19,270	144,300	10,710	18,130	135,800	10,070
27	0.8927	7.443	19,310	143,700	10,730	18,160	135,200	10,090
28	0.8871	7.396	19,350	143,100	10,750	18,190	134,600	10,110
29	0.8816	7.350	19,380	142,500	10,770	18,220	133,900	10,120
30	0.8762	7.305	19,420	141,800	10,790	18,250	133,300	10,140
31	0.8708	7.260	19,450	141,200	10,810	18,280	132,700	10,150
32	0.8654	7.215	19,490	140,600	10,830	18,310	132,100	10,170
33	0.8602	7.171	19,520	140,000	10,850	18,330	131,500	10,180
34	0.8550	7.128	19,560	139,400	10,860	18,360	130,900	10,200
35	0.8498	7.085	19,590	138,800	10,880	18,390	130,300	10,210
36	0.8448	7.043	19,620	138,200	10,900	18,410	129,700	10,230
37	0.8398	7.001	19,650	137,600	10,920	18,430	129,100	10,240
38	0.8348	6.960	19,680	137,000	10,940	18,460	128,500	10,260
39	0.8299	6.920	19,720	136,400	10,950	18,480	127,900	10,270
40	0.8251	6.879	19,750	135,800	10,970	18,510	127,300	10,280
41	0.8203	6.839	19,780	135,200	10,990	18,530	126,700	10,300
42	0.8155	6.799	19,810	134,700	11,000	18,560	126,200	10,310
43	0.8109	6.760	19,830	134,100	11,020	18,580	125,600	10,320
44	0.8063	6.722	19,860	133,500	11,030	18,600	125,000	10,330
45	0.8017	6.684	19,890	132,900	11,050	18,620	124,400	10,340
46	0.7972	6.646	19,920	132,400	11,070	18,640	123,900	10,360
47	0.7927	6.609	19,940	131,900	11,080	18,660	123,300	10,370
48	0.7883	6.572	19,970	131,200	11,100	18,680	122,800	10,380
49	0.7839	6.536	20,000	130,700	11,110	18,700	122,200	10,390

Attachment 3-11, Selected Coal Analysis[2]

Coal	Location	Moisture	Volatile Matter	Fixed Carbon	Ash	Sulfur	High Heating Value
Anthracite	Lackawanna Co., PA	2.5	6.2	79.4	11.9	0.60	12,925
Low-Vol. Bituminous	McDowell Co., WV	1.0	16.2	77.3	5.1	0.74	14,715
High-Vol. Bituminous	Westmoreland Co., PA	1.5	30.7	56.6	11.2	1.82	13,325
Subbituminous A	Musselshell Co., MT	14.1	32.2	46.7	7.0	0.43	11,140
Subbituminous C	Campbell Co., WY	31.0	31.4	32.8	4.8	0.55	8,320
Lignite A	Mercer Co., ND	37.0	37.0	32.2	4.2	0.40	7,255

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ANSWER SHEET for
#427 — Combustion Evaluation

Name: ______________________________

Part I True-False

1. T F
2. T F
3. T F
4. T F
5. T F
6. T F
7. T F
8. T F
9. T F
10. T F

Part II Multiple Choice

1. a b c d
2. a b c d
3. a b c d
4. a b c d
5. a b c d
6. a b c d
7. a b c d
8. a b c d
9. a b c d
10. a b c d
11. a b c d
12. a b c d
13. a b c d
14. a b c d
15. a b c d
16. a b c d

Part II (continued)

17. a b c d
18. a b c d
19. a b c d
20. a b c d
21. a b c d
22. a b c d
23. a b c d
24. a b c d
25. a b c d

Part III Fill in the Blank

1. ____________________
2. ____________________
3. ____________________

4.a ______________________________

b ______________________________

5.a ______________________________

b ______________________________

6.a ______________________________

b ______________________________

7. ______________________________

Part IV Problems

1. ____________________ ft^3
2. ____________________ ft^3
3. ____________________ gal/hr
4. ____________________ Btu/lb
5. ____________________ %

ANSWER SHEET for Post-Test
#427 — Combustion Evaluation

SCORE FOR POST-TEST

Name: ________________________________

Part I True-False

1. T [✓ F]

2. T [✓ F]

3. T [✓ F]

4. T [✓ F]

5. [✓ T] F

6. T [✓ F]

7. [✓ T] F

8. T [✓ F]

9. [✓ T] F

10. [✓ T] F

Part II Multiple Choice

1. a b c [✓ d]

2. a [✓ b] c d

3. a b [✓ c] d

4. a [✓ b] c d

5. a [✓ b] c d

6. a [✓ b] c d

7. [✓ a] b c d

8. a [✓ b] c d

9. a [✓ b] c d

10. a b [✓ c] d

11. a b [✓ c] d

12. a [✓ b] c d

13. a [✓ b] c d

14. a b [✓ c] d

15. a b [✓ c] d

16. a b [✓ c] d

Part II (continued)

17. a b [✓ c] d

18. a b c [✓ d]

19. a b c [✓ d]

20. [✓ a] b c d

21. a [✓ b] c d

22. a b [✓ c] d

23. a [✓ b] c d

24. a b [✓ c] d

25. [✓ a] b c d

Part III Fill in the Blank

1. ∿ 11,140 Btu/lb

2. ∿ 141,000 Btu/gal

3. ∿ 2.5%

4.a fixed carbon/ ash

b volatile matter; moisture

5.a more fuel NO_X

b use more excess air

6.a limit SO_3, NO_X

b improve efficiency

7. particulate emissions; also efficiency

Part IV Problems

1. 80 ft^3

2. 620 ft^3

3. 784 gal/hr

4. 3,620 Btu/lb

5. 98 %

#427 — COMBUSTION EVALUATION IN AIR POLLUTION CONTROL

POST-TEST

Note: The entire test is closed book. Each answer is worth 2 points. Enter all answers on the ANSWER SHEET provided.

Part I True-False

Note: For each of the following statements, circle on the answer sheet the letter T if the statement is True or the letter F if False.

1. T F The use of excess air to control furnace temperature always increases thermal efficiency.
2. T F The difference between the gross and net heating values of a fuel is related to the exhaust gas temperature.
3. T F At equilibrium the temperature is always the adiabatic flame temperature.
4. T F For best overall furnace performance, a gas flame should touch the heat transfer surface (tube/water wall).
5. T F All chemical reactions are reversible to some extent.
6. T F Direct-fired afterburners are no longer viable for controlling gaseous emissions, due to the shortage and cost of natural gas.
7. T F The region of stable gas flame operation is affected by the percentage of premixing.
8. T F If cracking of fuel oil droplets occurs, the flame will change from its normally yellow appearance to blue.
9. T F Lifting of flame zone can result when gas velocity exceeds the flame propagation velocity.
10. T F Catalytic incineration operates at considerably lower temperatures than direct-flame afterburners.

Part II Multiple Choice

Note: There is only one "best answer." Circle the proper letter on the answer sheet.

1. The emission factor for SO_2 is 38 S rather than 40 S because

   a some sulfur is not burned
   b some sulfur converts to SO_3
   c some sulfur may be collected with particulates by a precipitator
   d all of the above

2. The molecular weight of ethylene, C_2H_4, is 28, and the molecular weight of ethyl alcohol, C_2H_5OH, is 46. The amount of air required for complete combustion of 28 pounds of ethylene would be

   a less than the air required to burn 46 pounds of ethyl alcohol.
   b the same as the air required to burn 46 pounds of ethyl alcohol.
   c more than the air required to burn 46 pounds of ethyl alcohol.

3. The available heat from a combustion system is the

   a net heating value of the fuel less the flue gas losses.
   b gross heating value of the fuel less the heat content of combustion products at the adiabatic flame temperature.
   c gross heating value of the fuel plus the heat content of input fuel and air, less the flue gas losses.

4. The higher heating value is not equivalent to the

   a gross heat of combustion.
   b net heat of combustion.
   c gross calorific value.
   d total heat of combustion.

5. CO_2 is an important parameter in combustion control because CO_2 is an indication of

   a high combustion temperature.
   b excess air.
   c fuel burned.
   d dissociation.

6. Two-stage combustion may be accomplished by

   a turning up the primary air.
   b providing overfire air ports.
   c lean combustion followed by rich combustion.
   d increasing the underfire air.

7. Concentration standards may be expressed in

   a $\mu g/m^3$.
   b ton/hr.
   c million Btu/hr.
   d kg/hr.

8. An air preheater has the following effect on a combustion system

   a decreases efficiency.
   b increases efficiency.
   c requires more fuel.
   d produces less NO_x.

9. The Arrhenius equation permits the calculation of

   a the efficiency of a catalyst as a function of its surface.
   b the effect of temperature on the reaction rate.
   c utilization of stoichiometric air.

10. Temperature and residence time requirements for toxic chemicals (such as pesticides) in comparison to those for hydrocarbons of similar structure are

    a approximately the same.
    b considerably higher due to the presence of chlorine and nitrogen atoms.
    c considerably higher due to the need for higher destruction efficiencies for safety reasons.

11. Thermal incineration of combustible gaseous pollutants in low concentrations requires a combination of temperatures and residence times which, typically for hydrocarbon solvents, are

    a 500 to 1,000°F for 0.2 to 0.4 sec.
    b 1,600°F for 1 to 2 sec.
    c 1,200 to 1,400°F for 0.3 to 0.5 sec.

12. The proper equation to be used in correcting emissions to a 50% excess air basis is

    a $$F_{50} = 1 - \frac{1.5\ O_{2p} - 0.75\ CO_p}{.21}$$

    b $$F_{50} = 1 - \frac{1.5\ O_{2p} - 0.133\ N_{2p} - 0.75\ CO_p}{0.21}$$

    c $$F_{50} = \frac{(O_{2p} - 0.5\ CO_p) \times 100\%}{0.264\ N_{2p} - (O_{2p} - 0.5\ CO_p)}$$

13. The proper equation for determining the excess air from a flue gas Orsat analysis is

    a $$\%EA = \frac{0.21 - O_{2p}}{0.15}$$

    b $$\%EA = \frac{(O_{2p} - 0.5\ CO_p) \times 100\%}{0.264\ N_{2p} - (O_{2p} - 0.5\ CO_p)}$$

    c $$\%EA = \frac{CO_{2p}}{0.12}$$

14. A continuous source of ignition for oil firing is

- a more critical than for gas-fired units.
- b generally an electrode for a utility boiler.
- c generally an electrode for domestic units.
- d generally a pilot light for residential units.

15. Vanadium in fuel oil influences corrosion

- a of nozzles by forming a fuel acid.
- b by acting as a catalyst to shift NO_2 to NO_3.
- c by acting as a catalyst to shift SO_2 to SO_3.
- d changing the dew point.

16. More auxiliary fuel in the afterburner of a controlled-air incinerator is usually needed if the gas temperatures are

- a below 2,100°F.
- b below 1,700°F.
- c below 1,500°F.
- d above 1,700°F.

17. The ash fusion temperature of coal

- a is important when considering burning in a pulverized form.
- b should be low enough to form a good cake.
- c indicates the potential of forming clinkers or slag.
- d is lower than the ash-softening temperature.

18. An increase in a solid fuel's volatile matter

- a requires an increase of overfire air in stoker-fired systems.
- b increases the tendency to smoke.
- c implies a decrease in the solid fuel's residence time requirements.
- d all of the above.

19. A pulverized-coal furnace burning eastern coal would typically have a CO_2 level around

- a 5 to 10%.
- b 3 to 5%.
- c 20 to 25%.
- d 13 to 15%.

20. Thermal efficiency is generally improved with

- a less excess air than at the smoke limit.
- b flue gas recirculation.
- c reduced combustion air preheat.
- d more excess air than at the smoke limit.

21. "Lowest practical O_2"

- a is lower than the "minimum O_2."
- b provides for an operating margin below the smoke limit.
- c results in less smoke than at "minimum O_2."
- d results in more NO_x emissions than at "minimum O_2."

22. "Thermal NO_x" and "Fuel NO_x" have similarities because

- a the formation of each is directly related to temperature.
- b the formation of each is inversely related to temperature.
- c excess air is an effective control technique for each.
- d flue gas recirculation is an effective control technique for each.

23. A rotary-cup burner unit generally has greater particulate emissions than a mechanical atomizer unit because the

- a viscosity is too high.
- b drop sizes are too large.
- c residence time is too long.
- d the cup's edge is chipped.

24. Atomization size and pattern shape are

- a influenced only by oil pressure.
- b maintained by daily replacement of old nozzles with new nozzles on oil-fired utility units.
- c maintained by cleaning nozzles each shift on oil-fired utility units.
- d are about the same for all nozzles sold for residential units in the USA.

25. What is the maximum sulfur content for a 12° API fuel oil which must meet a 0.80 lb $SO_2/10^6$ Btu standard?

- a .75%.
- b 1.50%.
- c 1.00%.
- d 6.15%.

Part III Fill in the Blanks

1. Give a representative higher heating value for a western subbituminous coal: ______________ Btu/lb.

2. Give a representative value for the total heat of combustion for a No. 2 fuel oil: ______________ Btu/gal.

3. Give a representative moisture value for a typical eastern anthracite coal: ______________ %.

4. List two components in the proximate analysis: a ____________________
b ____________________

5. List two reasons why NO_x control from coal-fired boilers is more difficult than from similar oil or gas units:

a ____________________
b ____________________

6. Most larger furnaces burning fuel oil limit the excess air to around 2 to 5%, rather than 10 to 20% because of:

a ____________________
b ____________________

7. Reinjection of fly ash from stoker-fired units increases the ____________.

Part IV Problems

1. A certain mass of hydrogen occupies 100 ft^3 at 60°F and 1 atm. pressure. The temperature and pressure of the gas are increased to 580°F and 2.5 atm. What is the volume of hydrogen at the new condition? __________ ft^3.

2. For typical municipal solid waste having an as-fired heating value of 6,203 Btu/lb, calculate the furnace volume required per ton of waste per hour if a reasonable design is 20,000 Btu/hr ft^3: __________ ft^3.

3. If the energy output needed is 100 x 10^6 Btu/hr, calculate the oil-firing rate if the thermal efficiency is 85%, the heating value is 150,000 Btu/gal: __________ gal/hr.

4. If western hemlock has a dry heating value of 8,600 Btu/lb, calculate the as-fired heating value if the moisture as-fired is 57.9%: __________ Btu/lb.

5. A spreader stoker-fired furnace burns coal at a rate of 100 ton/hr. The coal has a gross heating value of 26,000,000 Btu/ton and a 10% ash content. Calculate the fly ash collector efficiency required to meet the Federal particulate emission standard of 0.1 pounds per million Btu. Note the uncontrolled emission factor for a spreader stoker is 13A (lbs/ton), where A is the percent of ash in the coal.

______________ % efficiency.

Attachment 3-1, Analyses of Samples of Natural Gas[2]

Sample No. Source of Gas	1 Pa.	2 So. Cal.	3 Ohio	4 La.	5 Okla.
Analyses					
Constituents, % by vol					
H_2 Hydrogen	—	—	1.82	—	—
CH_4 Methane	83.40	84.00	93.33	90.00	84.10
C_2H_4 Ethylene	—	—	0.25	—	—
C_2H_6 Ethane	15.80	14.80	—	5.00	6.70
CO Carbon monoxide	—	—	0.45	—	—
CO_2 Carbon dioxide	—	0.70	0.22	—	0.80
N_2 Nitrogen	0.80	0.50	3.40	5.00	8.40
O_2 Oxygen	—	—	0.35	—	—
H_2S Hydrogen sulfide	—	—	0.18	—	—
Ultimate, % by wt					
S Sulfur	—	—	0.34	—	—
H_2 Hydrogen	23.53	23.30	23.20	22.68	20.85
C Carbon	75.25	74.72	69.12	69.26	64.84
N_2 Nitrogen	1.22	0.76	5.76	8.06	12.90
O_2 Oxygen	—	1.22	1.58	—	1.41
Specific gravity (rel to air)	0.636	0.636	0.567	0.600	0.630
Higher heat value					
Btu/cu ft @ 60F & 30 in. Hg	1,129	1,116	964	1,002	974
Btu/lb of fuel	23,170	22,904	22,077	21,824	20,160

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Attachment 3-3, Detailed Requirements for Fuel Oils[1]

Grade of Fuel Oil[b]		Flash Point, F	Pour Point, F	Water and Sediment, per cent by volume	Carbon Residue on 10 per cent Bottoms per cent	Ash, per cent by weight	Distillation Temperatures, F			Saybolt Viscosity, sec				Kinematic Viscosity, centistokes				Gravity, deg API	Copper Strip Corrosion
							10 per cent Point	90 per cent Point		Universal at 100 F		Furol at 122 F		At 100 F		At 122 F			
		Min	Max	Max	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Min	Max
No. 1	A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	100 or legal	0	trace	0.15	...	420	550	...	...	...	...	...	2.2	1.4	...	...	35	No. 3
No. 2	A distillate oil for general purpose domestic heating for use in burners not requiring No. 1 fuel oil	100 or legal	20[c]	0.10	0.35	...	[d]	640[e]	540[e]	37.93	32.6	...	...	(3.6)[e]	(2.0)[e]	...	...	30[g]	...
No. 4	An oil for burner installations not equipped with preheating facilities	130 or legal	20	0.50	...	0.10	...	...	...	125	45	...	...	(26.4)	(5.8)		...	...	...
No. 5	A residual-type oil for burner installations equipped with preheating facilities	130 or legal	...	1.00	...	0.10	...	...	...	...	150	40	...	...	(32.1)	(81)	...	...	...
No. 6	An oil for use in burners equipped with preheaters permitting a high-viscosity fuel	150	...	2.00[f]	...	...				...	...	300	45	...	..	(638)	(92)		...

[a] Recognizing the necessity for low sulfur fuel oils used in connection with heat treatment, nonferrous metal, glass, and ceramic furnaces and other special uses, a sulfur requirement may be specified in accordance with the following table.

Grade of Fuel Oil	Sulfur, max. per cent
No. 1	0.5
No. 2	1.0
No. 4	no limit
No. 5	no limit
No. 6	no limit

Other sulfur limits may be specified only by mutual agreement between the purchaser and the seller.

[b] It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

[c] Lower or higher pour points may be specified whenever required by conditions of storage or use. However, these specifications shall not require a pour point lower than 0 F under any conditions.

[d] The 10 per cent distillation temperature point may be specified at 440 F maximum for use in other than atomizing burners.

[e] When pour point less than 0 F is specified, the minimum viscosity shall be 1.8 cs (32.0 sec, Saybolt Universal) and the minimum 90 per cent point shall be waived.

[f] The amount of water by distillation plus the sediment by extraction shall not exceed 2.00 per cent. The amount of sediment by extraction shall not exceed 0.50 per cent. A deduction in quantity shall be made for all water and sediment in excess of 1.0 per cent.

[g] In the states of Alaska, Arizona, California, Hawaii, Idaho, Nevada, Oregon, Utah and Washington, a minimum gravity of 28 deg API is permissible

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Attachment 3-4, Typical Analyses and Properties of Fuel Oils[1]

Grade	No 1 Fuel Oil	No. 2 Fuel Oil	No 4 Fuel Oil	No. 5 Fuel Oil	No. 6 Fuel Oil
Type	Distillate (Kerosene)	Distillate	Very Light Residual	Light Residual	Residual
Color	Light	Amber	Black	Black	Black
API gravity, 60 F	40	32	21	17	12
Specific gravity, 60 60 F	0.8251	0.8654	0.9279	0 9529	0 9861
Lb per U S. gallon, 60 F	6.870	7.206	7.727	7.935	8 212
Viscos., Centistokes, 100 F	1.6	2.68	15.0	50 0	360 0
Viscos., Saybolt Univ., 100 F	31	35	77	232	—
Viscos., Saybolt Furol, 122 F	—	—	—	—	170
Pour point, F	Below zero	Below zero	10	30	65
Temp. for pumping, F	Atmospheric	Atmospheric	15 min.	35 min.	100
Temp. for atomizing, F	Atmospheric	Atmospheric	25 min.	130	200
Carbon residue per cent	Trace	Trace	2 5	5 0	12 0
Sulfur, per cent	0 1	0 4 0 7	0.4 1 5	2.0 max.	2 8 max.
Oxygen and nitrogen, per cent	0.2	0.2	0.48	0.70	0.92
Hydrogen, per cent	13.2	12 7	11 9	11.7	10.5
Carbon, per cent	86 5	85 4	86.10	85.55	85.70
Sediment and water, per cent	Trace	Trace	0.5 max.	1 0 max.	2 0 max.
Ash, per cent	Trace	Trace	0.02	0 05	0.08
Btu per gallon	137,000	141,000	146,000	148,000	150,000

* Technical information from Humble Oil & Refining Company.

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Attachment 3-5, Gravities, Densities, and Heats of Combustion of Fuel Oils[6]

VALUES FOR 10 TO 49 DEG API, INCLUSIVE, REPRINTED FROM BUREAU OF STANDARDS MISCELLANEOUS PUBLICATION NO. 97, "THERMAL PROPERTIES OF PETROLEUM PRODUCTS."

GRAVITY AT 60/60 F		DENSITY AT 60 F	TOTAL HEAT OF COMBUSTION (At Constant Volume)			NET HEAT OF COMBUSTION (At Constant Pressure)		
DEG API	SPECIFIC GRAVITY	LB PER GAL	BTU PER LB	BTU PER GAL AT 60 F	CAL PER G	BTU PER LB	BTU PER GAL AT 60 F	CAL PER G
5	1.0366	8.643	18,250	157,700	10,140	17,290	149,400	9,610
6	1.0291	8.580	18,330	157,300	10,180	17,340	148,800	9,650
7	1.0217	8.518	18,390	156,600	10,210	17,390	148,100	9,670
8	1.0143	8.457	18,440	155,900	10,240	17,440	147,500	9,700
9	1.0071	8.397	18,490	155,300	10,270	17,490	146,900	9,720
10	1.0000	8.337	18,540	154,600	10,300	17,540	146,200	9,740
11	0.9930	8.279	18,590	153,900	10,330	17,580	145,600	9,770
12	0.9861	8.221	18,640	153,300	10,360	17,620	144,900	9,790
13	0.9792	8.164	18,690	152,600	10,390	17,670	144,200	9,810
14	0.9725	8.108	18,740	152,000	10,410	17,710	143,600	9,840
15	0.9659	8.053	18,790	151,300	10,440	17,750	142,900	9,860
16	0.9593	7.998	18,840	150,700	10,470	17,790	142,300	9,880
17	0.9529	7.944	18,890	150,000	10,490	17,820	141,600	9,900
18	0.9465	7.891	18,930	149,400	10,520	17,860	140,900	9,920
19	0.9402	7.839	18,980	148,800	10,540	17,900	140,300	9,940
20	0.9340	7.787	19,020	148,100	10,570	17,930	139,600	9,960
21	0.9279	7.736	19,060	147,500	10,590	17,960	139,000	9,980
22	0.9218	7.686	19,110	146,800	10,620	18,000	138,300	10,000
23	0.9159	7.636	19,150	146,200	10,640	18,030	137,700	10,020
24	0.9100	7.587	19,190	145,600	10,660	18,070	137,100	10,040
25	0.9042	7.538	19,230	145,000	10,680	18,100	136,400	10,050
26	0.8984	7.490	19,270	144,300	10,710	18,130	135,800	10,070
27	0.8927	7.443	19,310	143,700	10,730	18,160	135,200	10,090
28	0.8871	7.396	19,350	143,100	10,750	18,190	134,600	10,110
29	0.8816	7.350	19,380	142,500	10,770	18,220	133,900	10,120
30	0.8762	7.305	19,420	141,800	10,790	18,250	133,300	10,140
31	0.8708	7.260	19,450	141,200	10,810	18,280	132,700	10,150
32	0.8654	7.215	19,490	140,600	10,830	18,310	132,100	10,170
33	0.8602	7.171	19,520	140,000	10,850	18,330	131,500	10,180
34	0.8550	7.128	19,560	139,400	10,860	18,360	130,900	10,200
35	0.8498	7.085	19,590	138,800	10,880	18,390	130,300	10,210
36	0.8448	7.043	19,620	138,200	10,900	18,410	129,700	10,230
37	0.8398	7.001	19,650	137,600	10,920	18,430	129,100	10,240
38	0.8348	6.960	19,680	137,000	10,940	18,460	128,500	10,260
39	0.8299	6.920	19,720	136,400	10,950	18,480	127,900	10,270
40	0.8251	6.879	19,750	135,800	10,970	18,510	127,300	10,280
41	0.8203	6.839	19,780	135,200	10,990	18,530	126,700	10,300
42	0.8155	6.799	19,810	134,700	11,000	18,560	126,200	10,310
43	0.8109	6.760	19,830	134,100	11,020	18,580	125,600	10,320
44	0.8063	6.722	19,860	133,500	11,030	18,600	125,000	10,330
45	0.8017	6.684	19,890	132,900	11,050	18,620	124,400	10,340
46	0.7972	6.646	19,920	132,400	11,070	18,640	123,900	10,360
47	0.7927	6.609	19,940	131,900	11,080	18,660	123,300	10,370
48	0.7883	6.572	19,970	131,200	11,100	18,680	122,800	10,380
49	0.7839	6.536	20,000	130,700	11,110	18,700	122,200	10,390

Post-Test 10

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Attachment 3-11, Selected Coal Analysis[2]

Coal	Location	Moisture	Volatile Matter	Fixed Carbon	Ash	Sulfur	High Heating Value
Anthracite	**Lackawanna Co., PA**	2.5	6.2	79.4	11.9	0.60	12,925
Low-Vol. Bituminous	**McDowell Co., WV**	1.0	16.2	77.3	5.1	0.74	14,715
High-Vol. Bituminous	**Westmoreland Co., PA**	1.5	30.7	56.6	11.2	1.82	13,325
Subbituminous A	**Musselshell Co., MT**	14.1	32.2	46.7	7.0	0.43	11,140
Subbituminous C	**Campbell Co., WY**	31.0	31.4	32.8	4.8	0.55	8,320
Lignite A	**Mercer Co., ND**	37.0	37.0	32.2	4.2	0.40	7,255

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ANSWER SHEET for
#427 — Combustion Evaluation

Name: ____________________

Part I True-False

1. T F
2. T F
3. T F
4. T F
5. T F
6. T F
7. T F
8. T F
9. T F
10. T F

Part II Multiple Choice

1. a b c d
2. a b c d
3. a b c d
4. a b c d
5. a b c d
6. a b c d
7. a b c d
8. a b c d
9. a b c d
10. a b c d
11. a b c d
12. a b c d
13. a b c d
14. a b c d
15. a b c d
16. a b c d

Part II (continued)

17. a b c d
18. a b c d
19. a b c d
20. a b c d
21. a b c d
22. a b c d
23. a b c d
24. a b c d
25. a b c d

Part III Fill in the Blank

1. ____________________
2. ____________________
3. ____________________
4.a ____________________
b ____________________
5.a ____________________
b ____________________
6.a ____________________
b ____________________
7. ____________________

Part IV Problems

1. ____________________ ft^3
2. ____________________ ft^3
3. ____________________ gal/hr
4. ____________________ Btu/lb
5. ____________________ %